LOW LEVEL - HIGH LEVEL

HOW AND WHY THE RF SYSTEM

HAS CHANGED AT INFN-LNS

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ECPM 2017

European Cyclotron Progress Meeting

The INFN-LNS RF system can be considered a sort of continuous work in progress, since the commissioning of the k-800 superconducting cyclotron, more than 20 years ago.

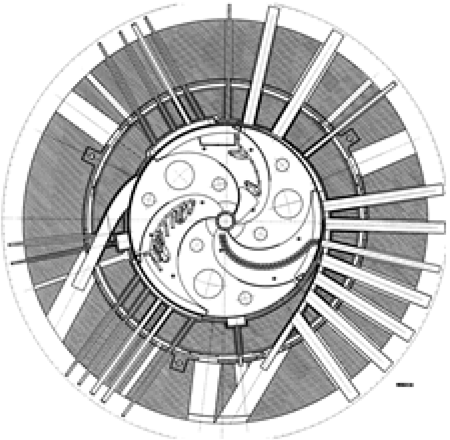
We would like to show the most important changes, upgrades and improvements of the entire RF system

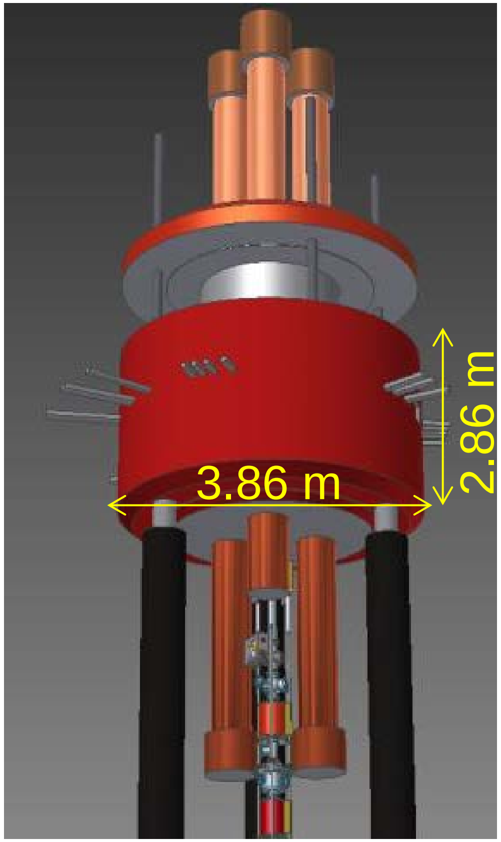
- some of the improvements are related to the system's age, to the outmodedness of important spare parts, like in the case of the High Level System;
- some are related to modifying the system to achieve better performance, like in a few mechanical components of the cavities;
- Some improvements regard the low level system, to keep up with electronic innovations and, more importantly, to follow the requests and suggestions of the accelerator operators, in order to have, especially in the phase of tuning the entire cyclotron, a clear RF control panel where all the main parameters are displayed and the RF operation becomes easy, intuitive and, in the event of failures, the feedback is immediate

Talking points

- Overview of the k-800 superconducting cyclotron and RF system
- Coupling capacitor, disk vs cylindrical ceramic insulator
- Axial injection vs radial injection
- Copper Dees vs Aluminium Dees
- Something around main ceramic insulator of the coaxial resonator (superconducting cyclotron upgrade)
- Sliding short circuits, drivers and movement mechanics
- Power coaxial switches between amplifiers and cavities
- Low Level and the digital RF box
- Hybrid configuration, solid state – tube to revamps an obsolete amplifier (improving output power of 20-30% for cyclotron upgrade)

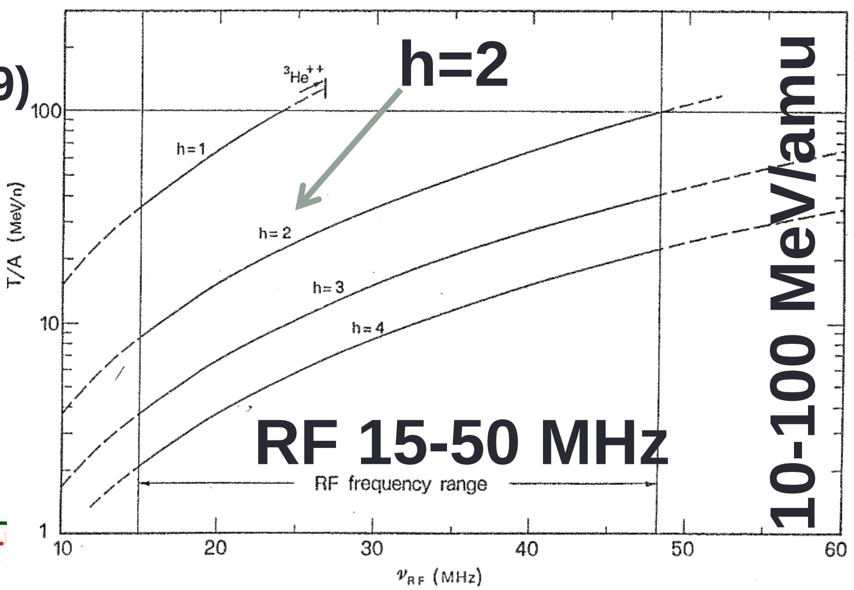
The K-800 Superconducting Cyclotron



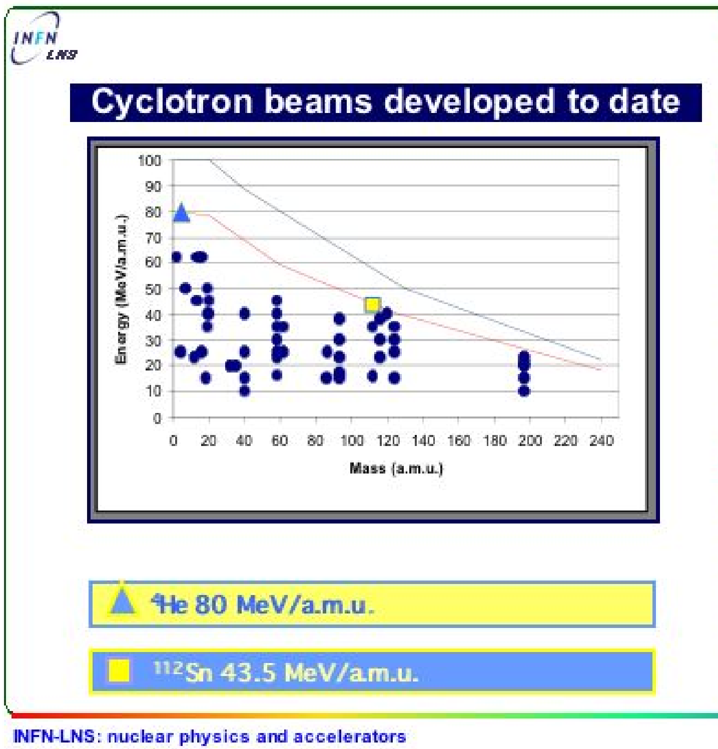


Bending limit	K=800
Focusing limit	Kfoc=200
Pole radius	90 cm
Yoke outer radius	190.3 cm
Yoke full height	286 cm
Total weight	176 tons
Min-Max field	2.2-4.8 Tesla
Main coil A/turn	6.5 10^6
Sectors	3
Min. hill gap	8.6 cm
Max valley gap	91.6 cm
Trim coils	20
Dees	3
RF range	15-50 MHz
Operating Harmonics	1,2,3,4
Peak dee voltage	100 KV

The introduction of the axial injection (1999) and the consequent new design of the central region geometry has meant the cyclotron operates in constant orbit mode with the harmonic mode of acceleration h=2 only.

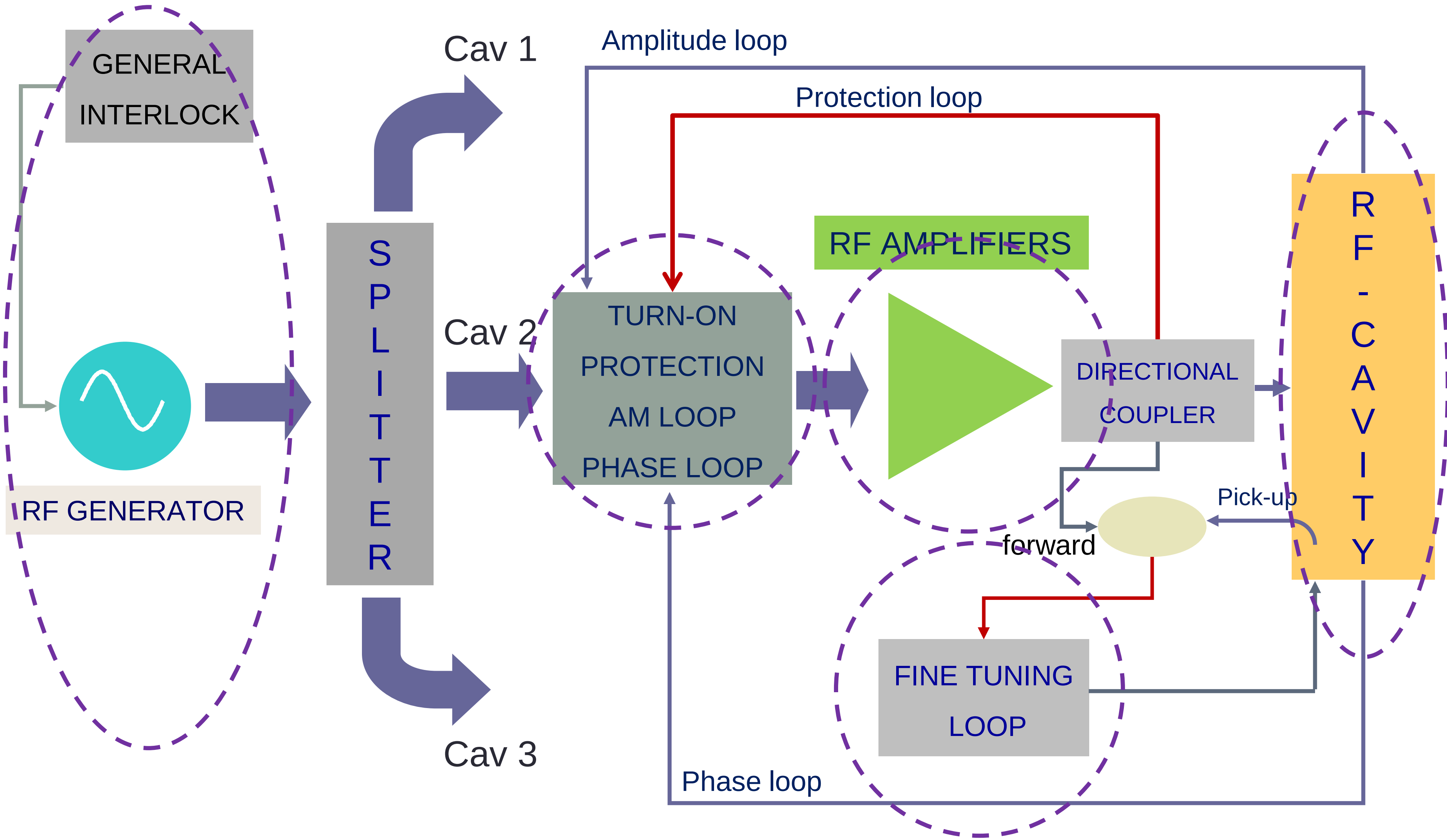


The operative diagram shows the ions energy as a function of the accelerating frequency for the original four harmonic modes.



^AX	E (MeV/a.m.
$^1H_2^+$	62,80
$^1H_3^+$	45
$^2H^+$	35,62,80
^4He	25,80
He-H	21
^9Be	45
^{12}C	23,62,80
^{13}C	45
^{14}N	62,80
^{16}O	21,25,62,80
^{18}O	15
^{19}F	35,40,50
^{20}Ne	21,40,45,62
^{32}S	19.5
^{35}Cl	19.5
^{36}Ar	16,38
^{40}Ar	15,21,40
^{40}Ca	10,25,40,45
^{48}Ca	10,45
^{58}Ni	16,23,25,30,35,40,45
^{62}Ni	25,35
^{86}Kr	15,21,25
^{93}Nb	15,17,23,30,38
^{112}Sn	15.5,35,43.5
^{116}Sn	23,30,38
^{120}Sn	40
^{124}Sn	15,25,30,35
^{129}Xe	21,23
^{197}Au	10,15,20,21,23

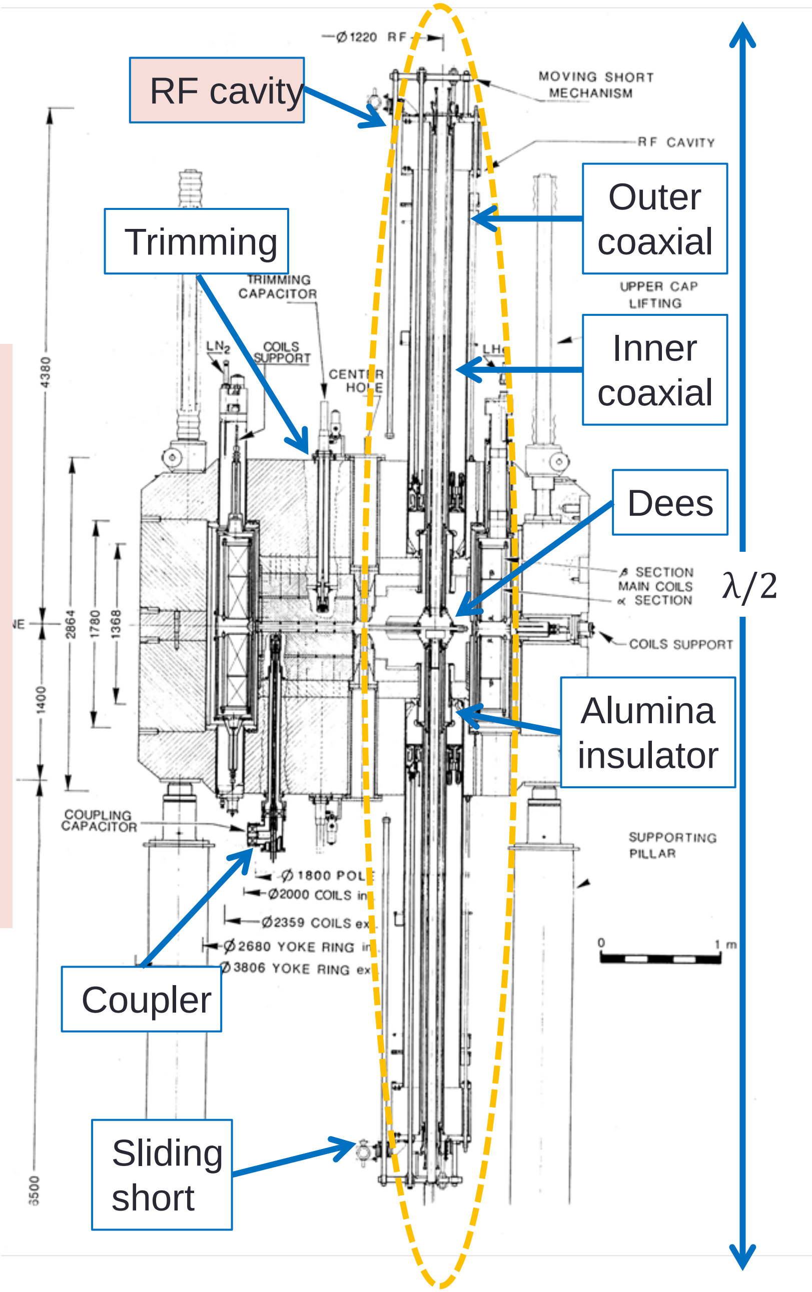
The general RF system block diagram



The core of RF System

The core RF system consists of three symmetrical coaxial resonators. Each resonator is two vertical ¼ λ cylindrical cavities connected at the centre by Dees placed in valleys.

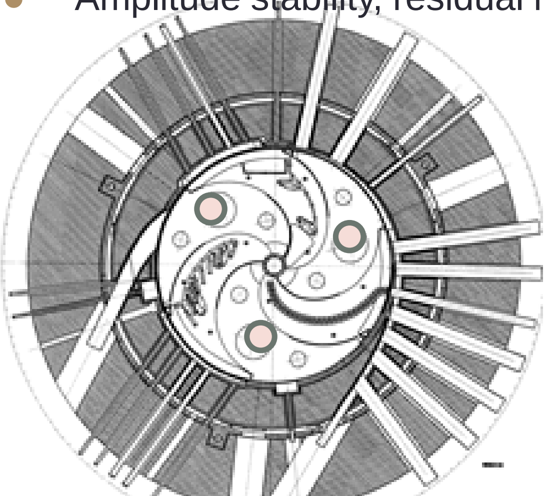
R F C A V I T Y



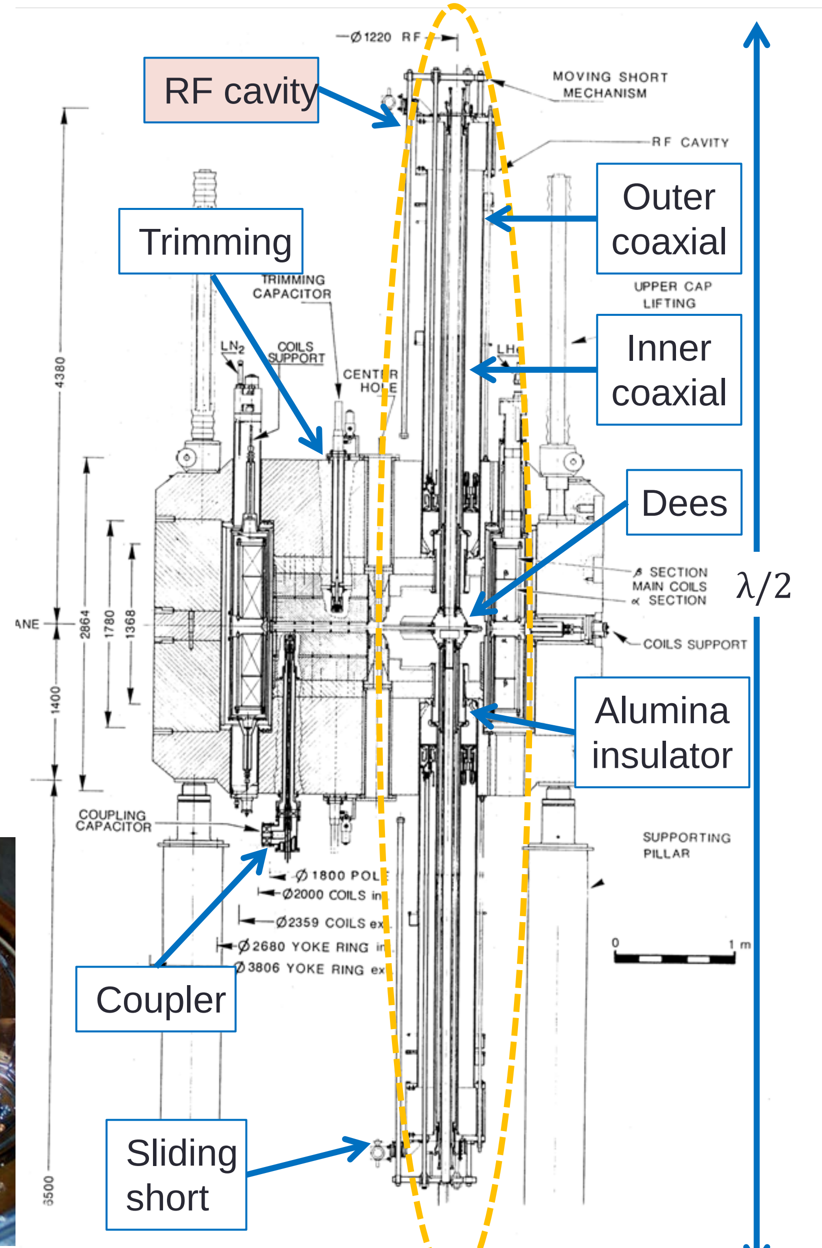
VERTICAL CROSS SECTION OF THE RF CAVITY

Main characteristics

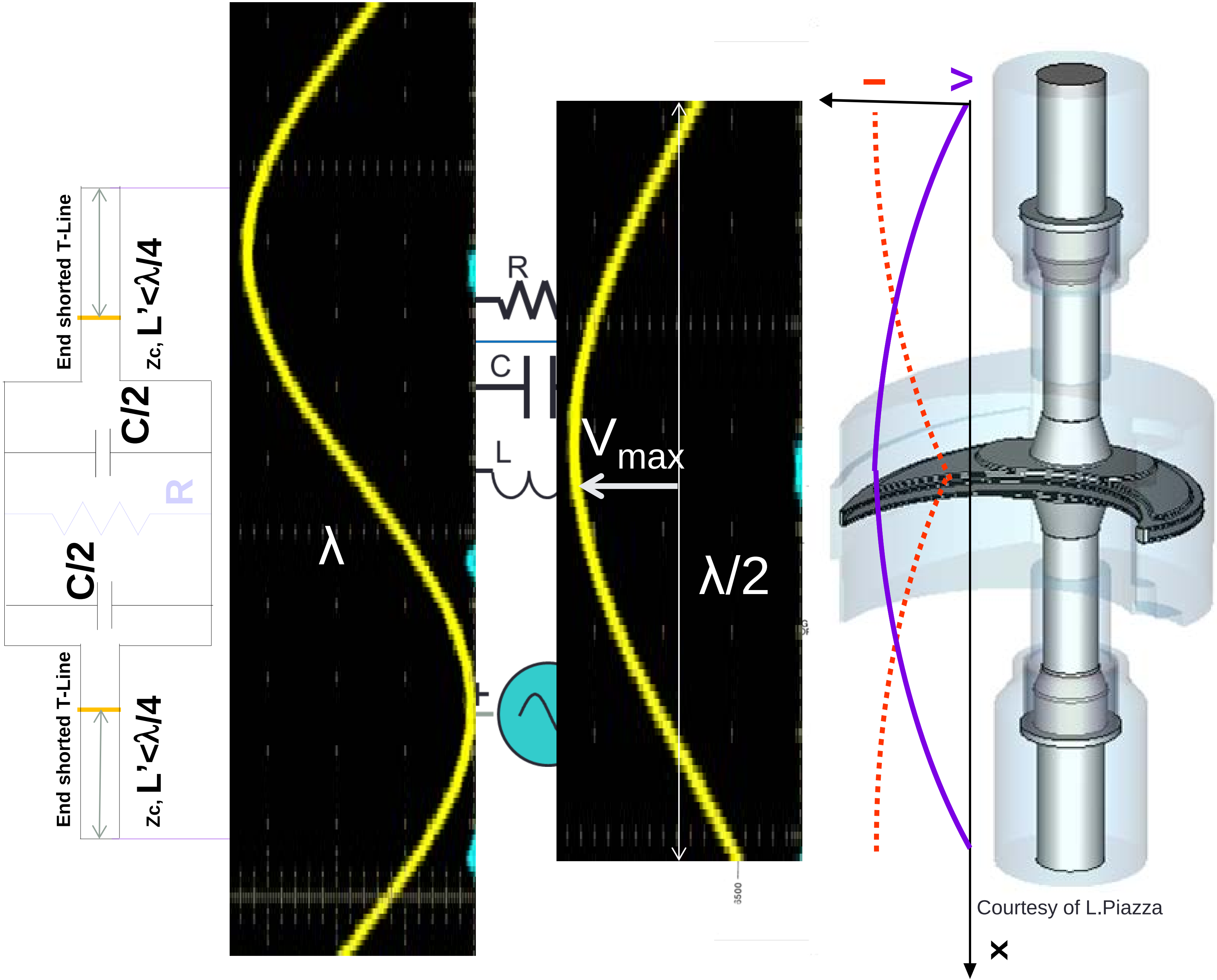
- Frequency range between 15 - 50 MHz
- ½ λ coaxial resonators (¼λ + dee + ¼λ)
- Tunable sliding shorts (0.85 – 3.5 m)
- Ceramic insulator (air-vacuum accelerator chamber)
- Q = 2000 - 5000
- Coupling capacitors to feed the power
- Maximum Voltage on the 3 dees, 100kV
- 120° phase difference between the dees
- Phase stability ± 0.1°
- Amplitude stability, residual noise $\leq 10^{-4}$



HORIZONTAL CROSS SECTION OF THE CAVITY

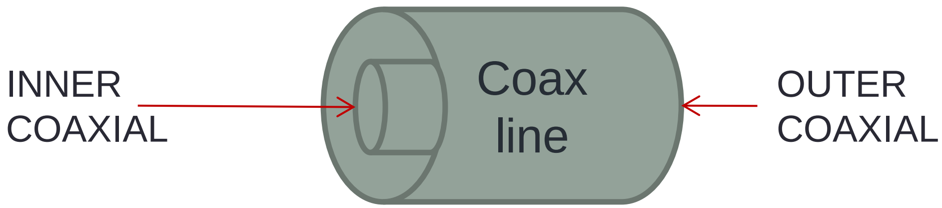


VERTICAL CROSS SECTION OF THE RF CAVITY

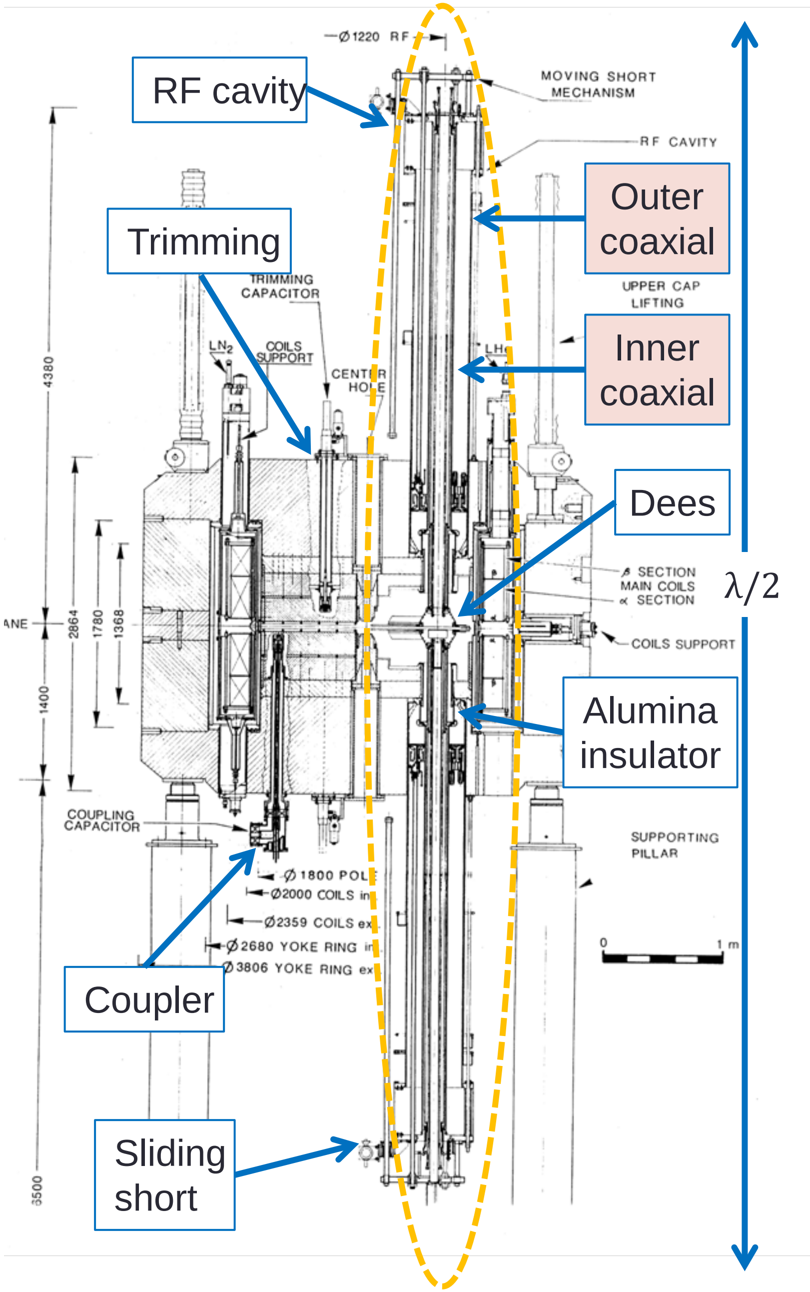


Courtesy of L.Piazza

The coaxial resonator



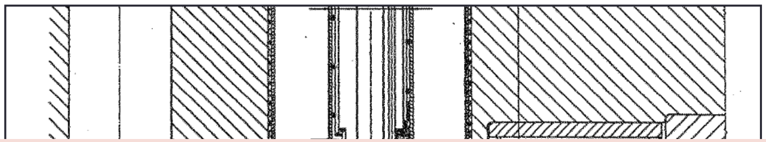
- Copper made
- Thickness of the surfaces 8 mm
- Inner-outer coax diameter 208 - 486 mm
- Inner coax manufactured, cold-drawing starting with oxygen-free copper billets
- Outer coaxial has been electroformed
- Outer coaxial are cooled by a parallel series of flat pipes soft soldered on the external surface
- Inner coaxial is cooled by a coaxial tube system where a special rubber seal drives the water flow



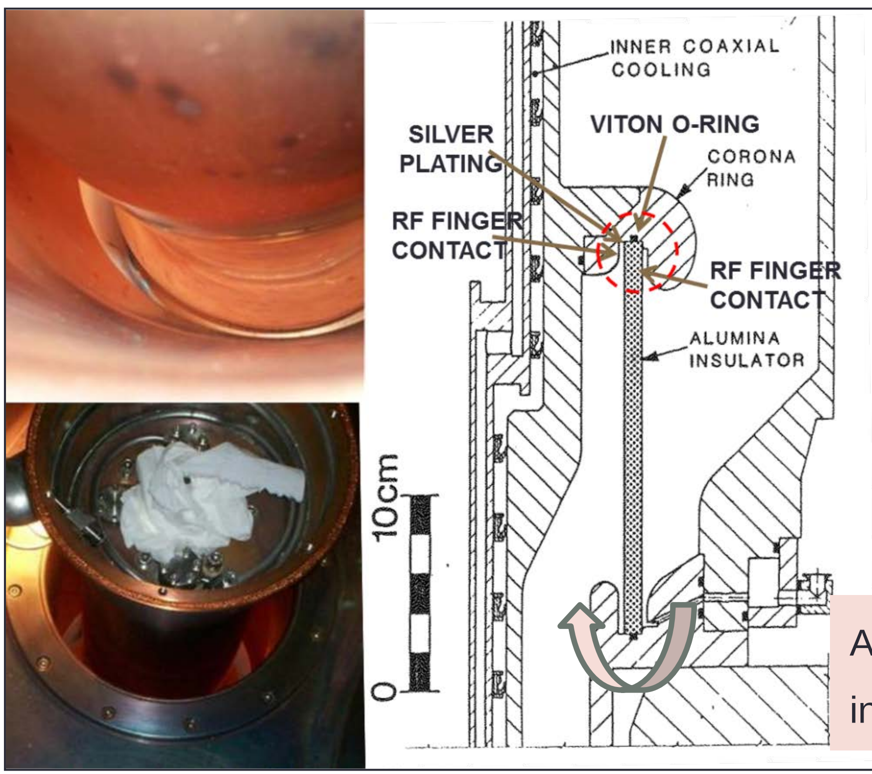
The high voltage ceramic insulator

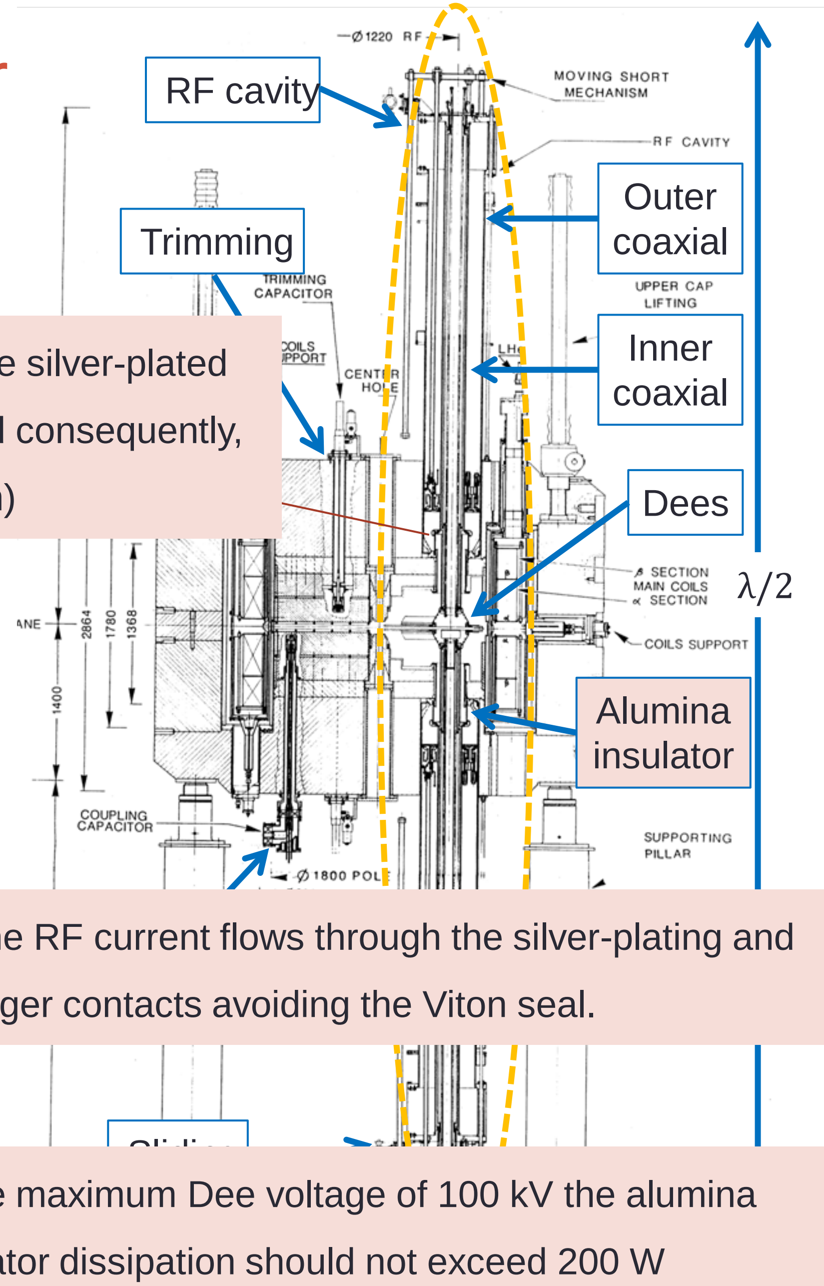
Question mark?

The high voltage ceramic insulator



Both U-shaped edges of the pure alumina (99.7%) insulator are silver-plated (0.4 mm thickness). This avoids the use of metallic sealing and consequently, any mechanical compression on the ceramic edges (>40kg/cm)



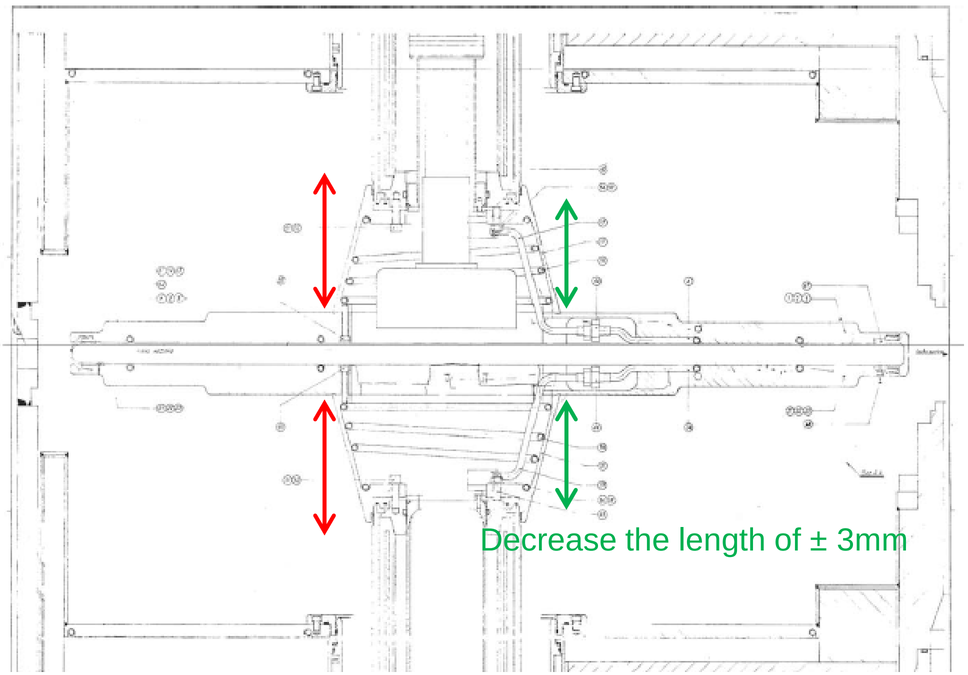


The RF current flows through the silver-plating and finger contacts avoiding the Viton seal.

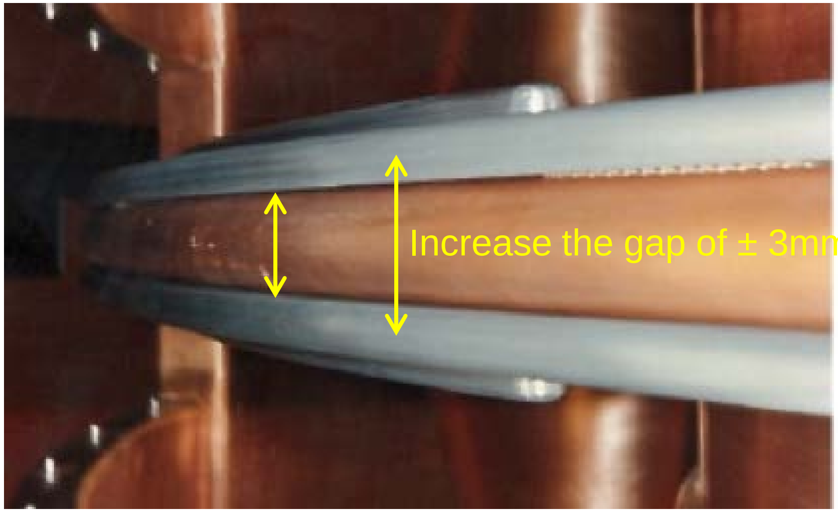
At the maximum Dee voltage of 100 kV the alumina insulator dissipation should not exceed 200 W

Up-grade of LNS superconducting cyclotron

Due to the different size of the beam, the vertical gap has to be increased from 24 to 30 mm, 6 mm of difference, 3mm up and 3 mm down. In first approximation, to reduce machinery, cost, complexity of the operation, we would like to take into exam the length reduction of the conical connection between the stem (inner coaxial) and the dee.



Dee will be much closer to the liner of 3 mm, if the conical length is reduced.



Upgrading of the LNS Superconducting Cyclotron to deliver beam power higher than 2-5 kW
Speaker:
Luciano Calabretta (LNS)

A specific and detailed study has been adopted to the upper and lower nose shape in order to have a low
voltage gradient at the insulator edges with a semi-uniform electric field distribution along the ceramic itself. At the maximum Dee voltage of 100 kV the insulator dissipation should not exceed 200 W [5]. Both U-shaped edges of the pure alumina (99.7%) insulator are silver-plated (0.4 mm thickness). This avoids the use of metallic sealing and consequently, any mechanical compression on the ceramic edges (> 40kg/cm). In Figure 1, the dotted red circle detail shows the silver-plating upper ceramic insulator edge, the Viton seal, the finger contacts position. The RF current flows through the silver-plating and finger contacts avoiding the Viton seal.[1][2]

[1] C. Pagani et al, Full power test of the first RF cavity for the Milan K800 Cyclotron, Japan 1986, p.271.
[2] A. Caruso, THE RF SYSTEM OF THE K-800 SUPERCONDUCTING CYCLOTRON AT INFN-LNS, India 2014

I wonder, if the proposed length reduction, of ±3mm (up and down), of the conical connection (dee-inner coax), can be accepted, in terms of maximum electric field distribution, around the critical zone of the nose. What do you think? Probably some CST/microwave studio numerical simulations are necessary…

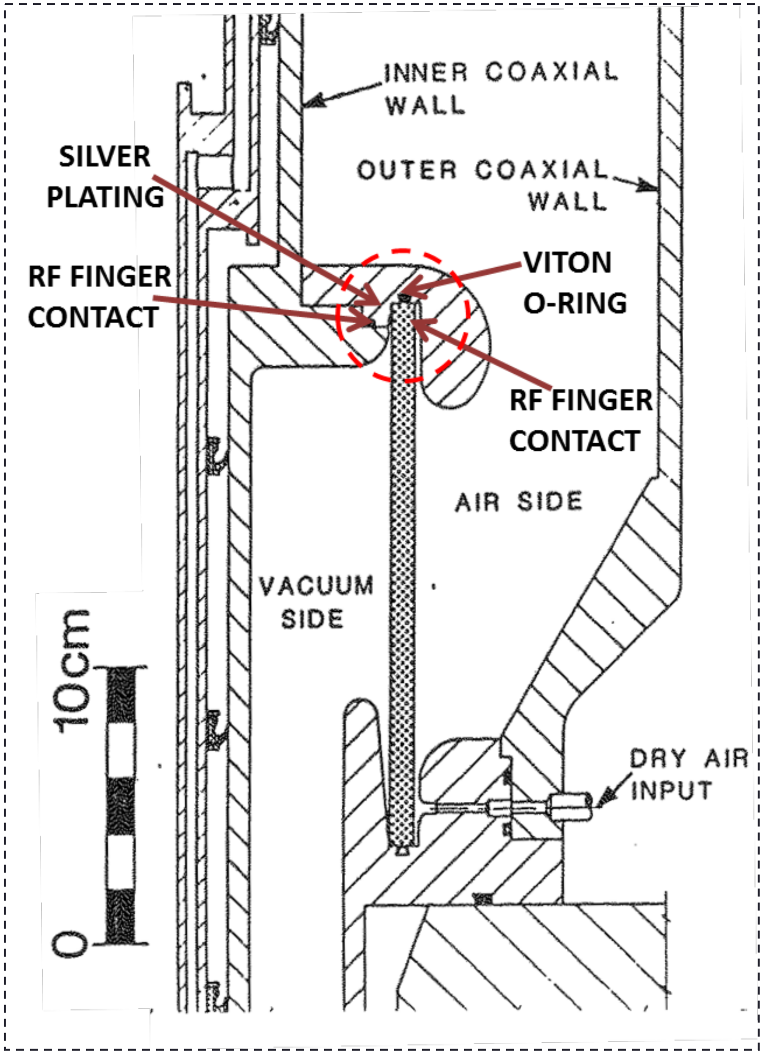
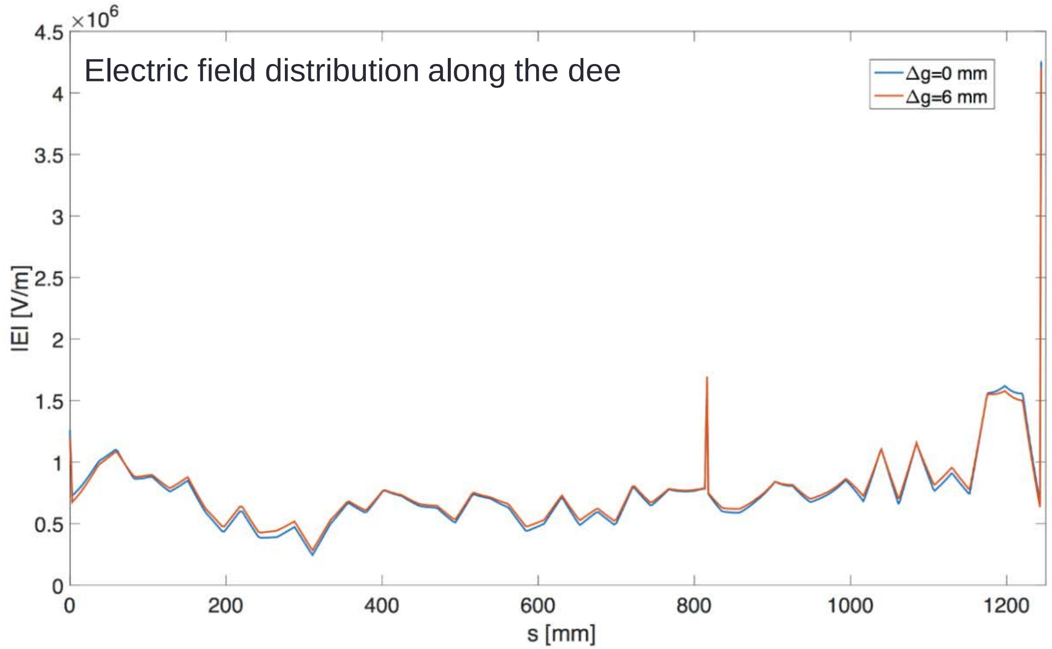
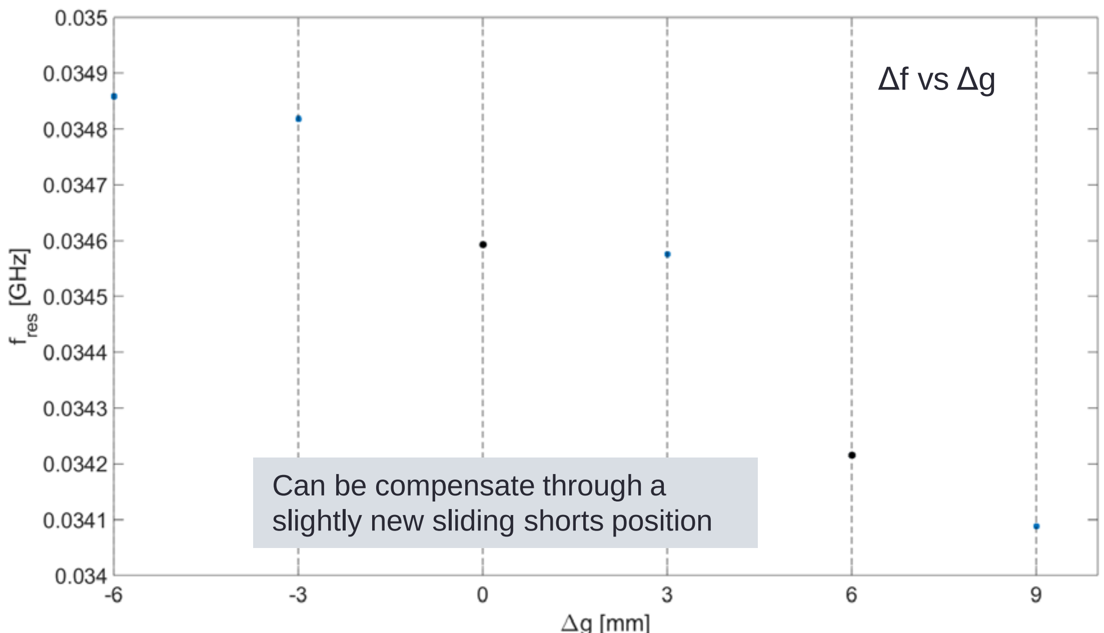
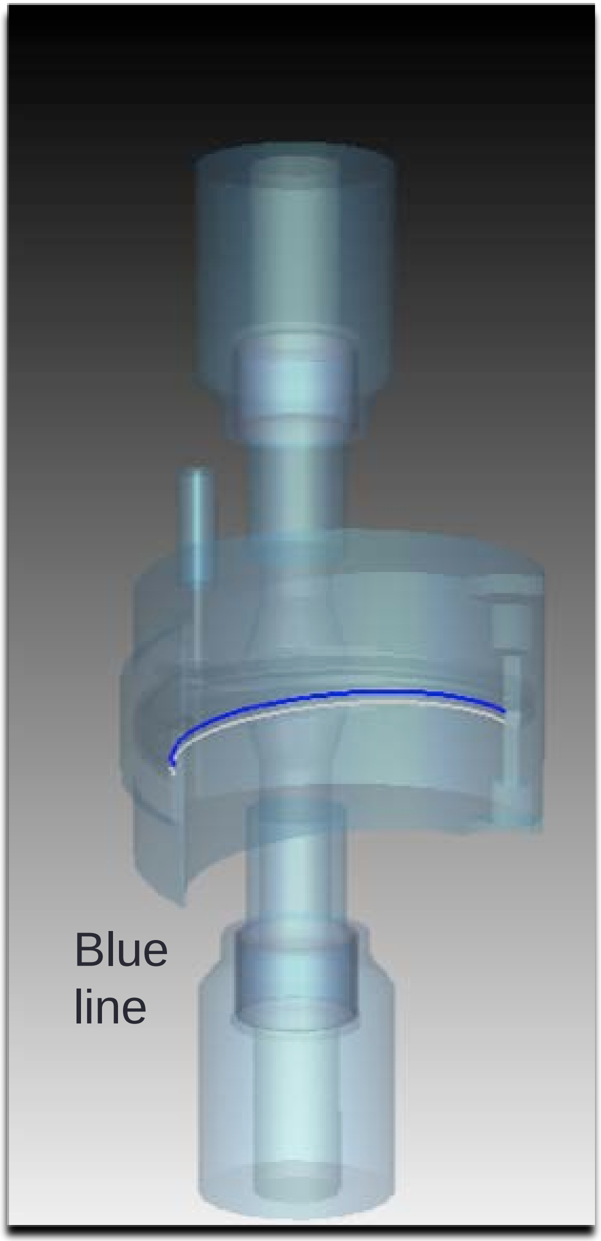


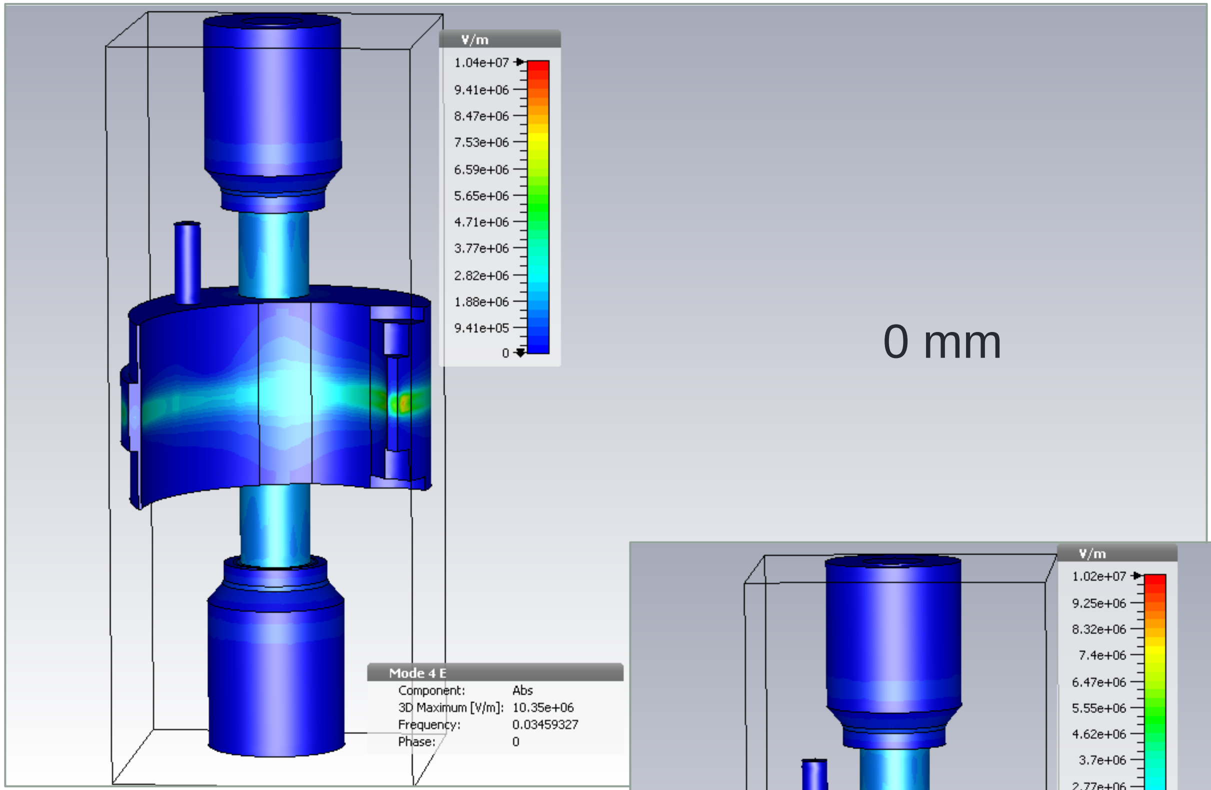
Figure 1



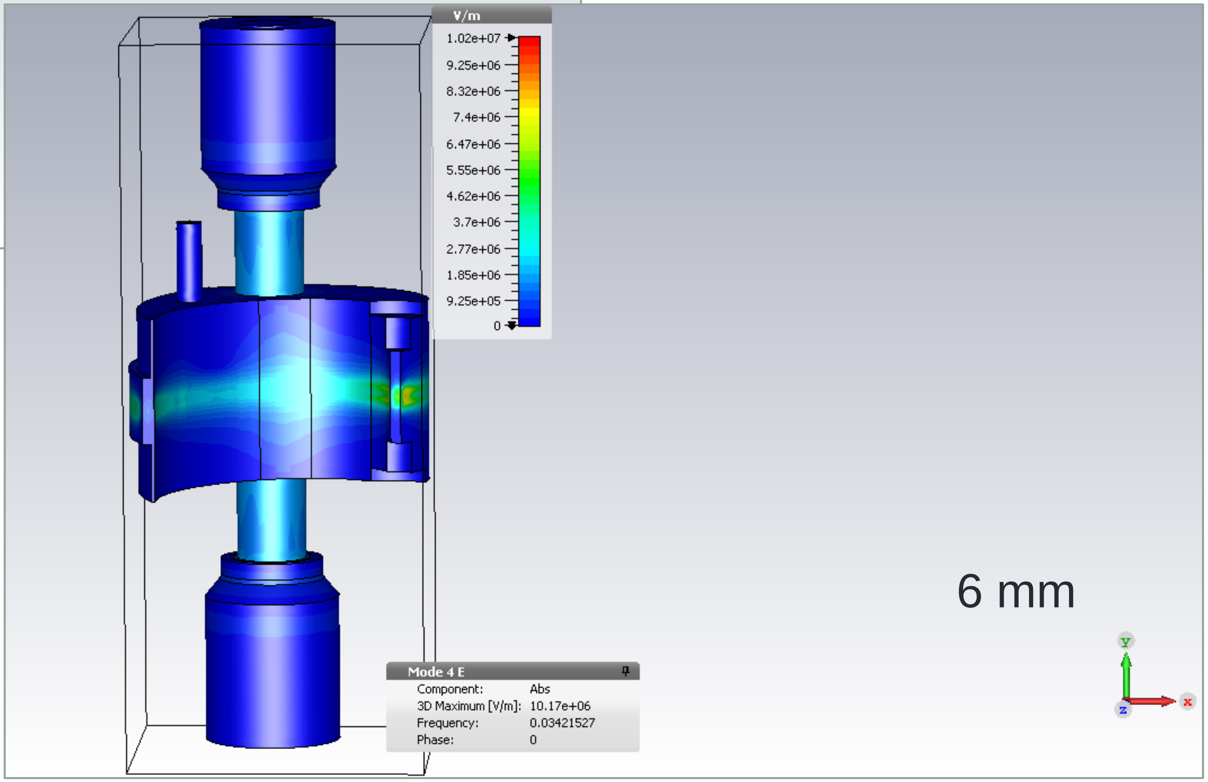




Courtesy of M. Maggiore

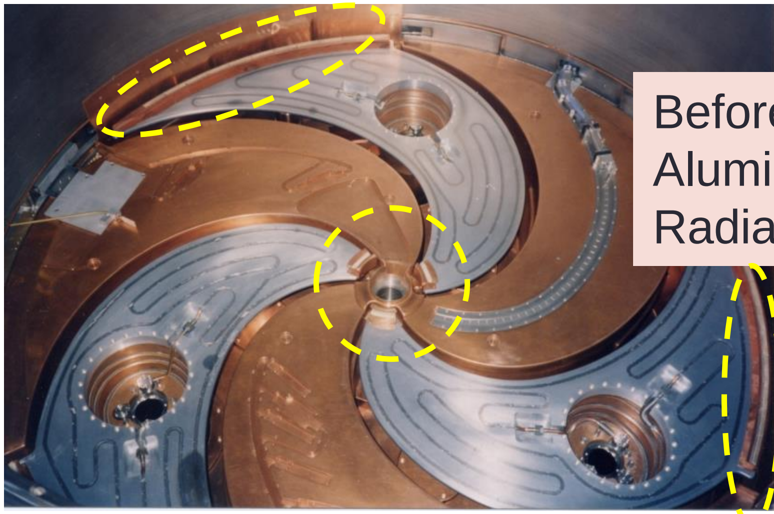

V/m
1.04e+07
9.41e+06
8.47e+06
7.53e+06
6.59e+06
5.65e+06
4.71e+06
3.77e+06
2.82e+06
1.88e+06
9.41e+05
0
Mode 4 E
Component: Abs
3D Maximum [V/m]: 10.35e+06
Frequency: 0.03459327
Phase: 0

0 mm

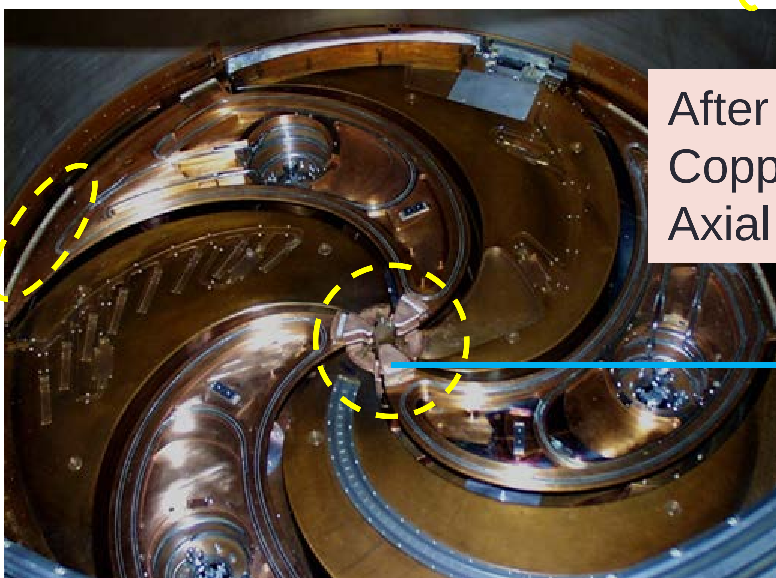

V/m
1.02e+07
9.25e+06
8.32e+06
7.4e+06
6.47e+06
5.55e+06
4.62e+06
3.7e+06
2.77e+06
1.85e+06
9.25e+05
0
Mode 4 E
Component: Abs
3D Maximum [V/m]: 10.17e+06
Frequency: 0.03421527
Phase: 0
Y
X
Z

6 mm

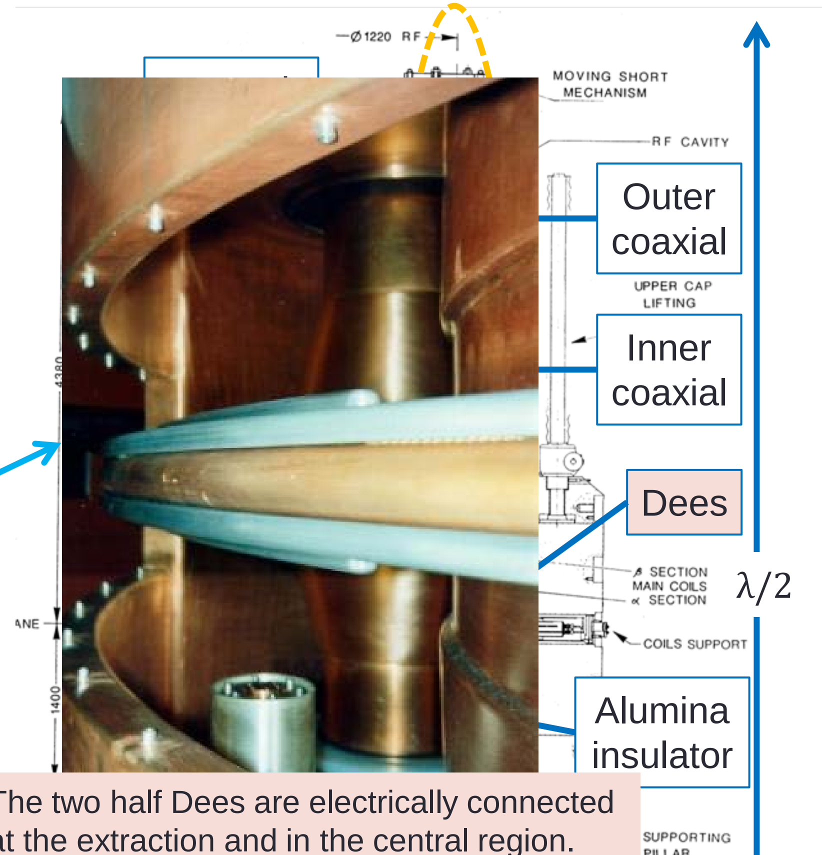
The DEES



Before 1999
Aluminium Dees
Radial injection



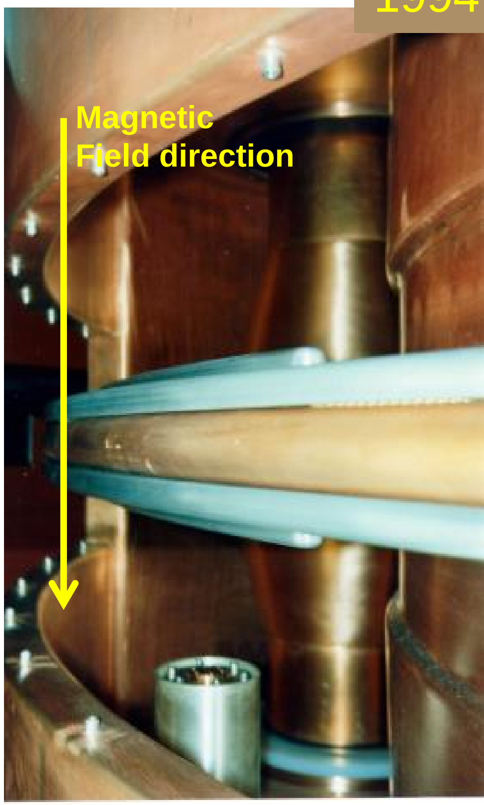
After 1999
Copper Dees
Axial injection

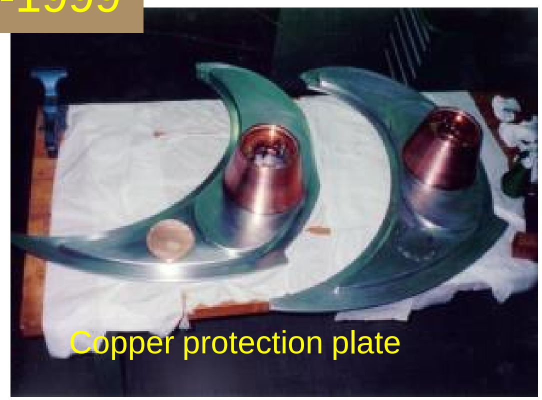


The two half Dees are electrically connected at the extraction and in the central region.

Trouble spot dees

1994 -1999



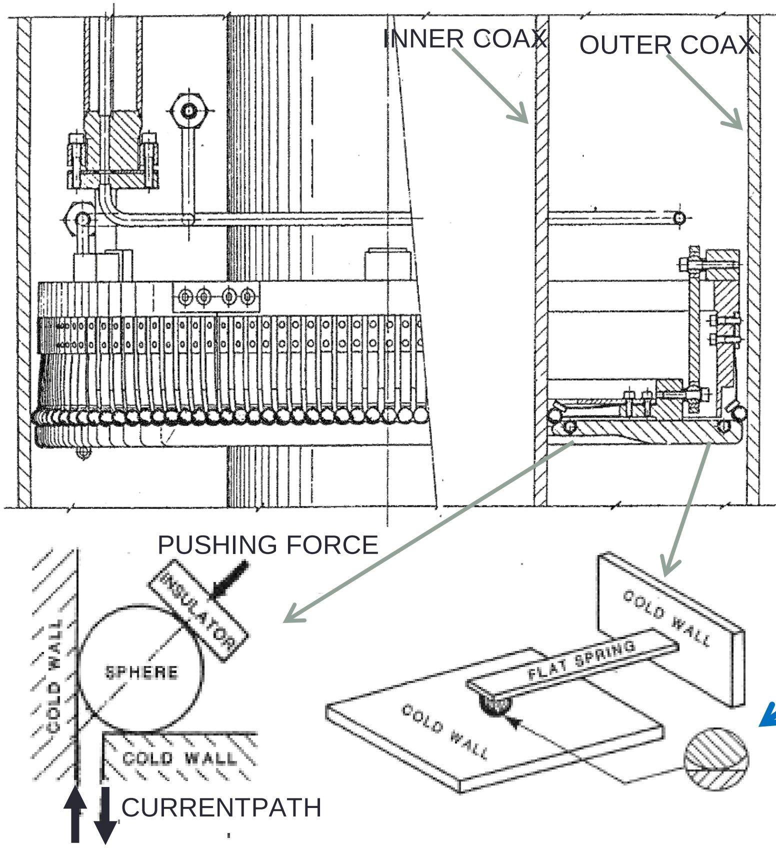


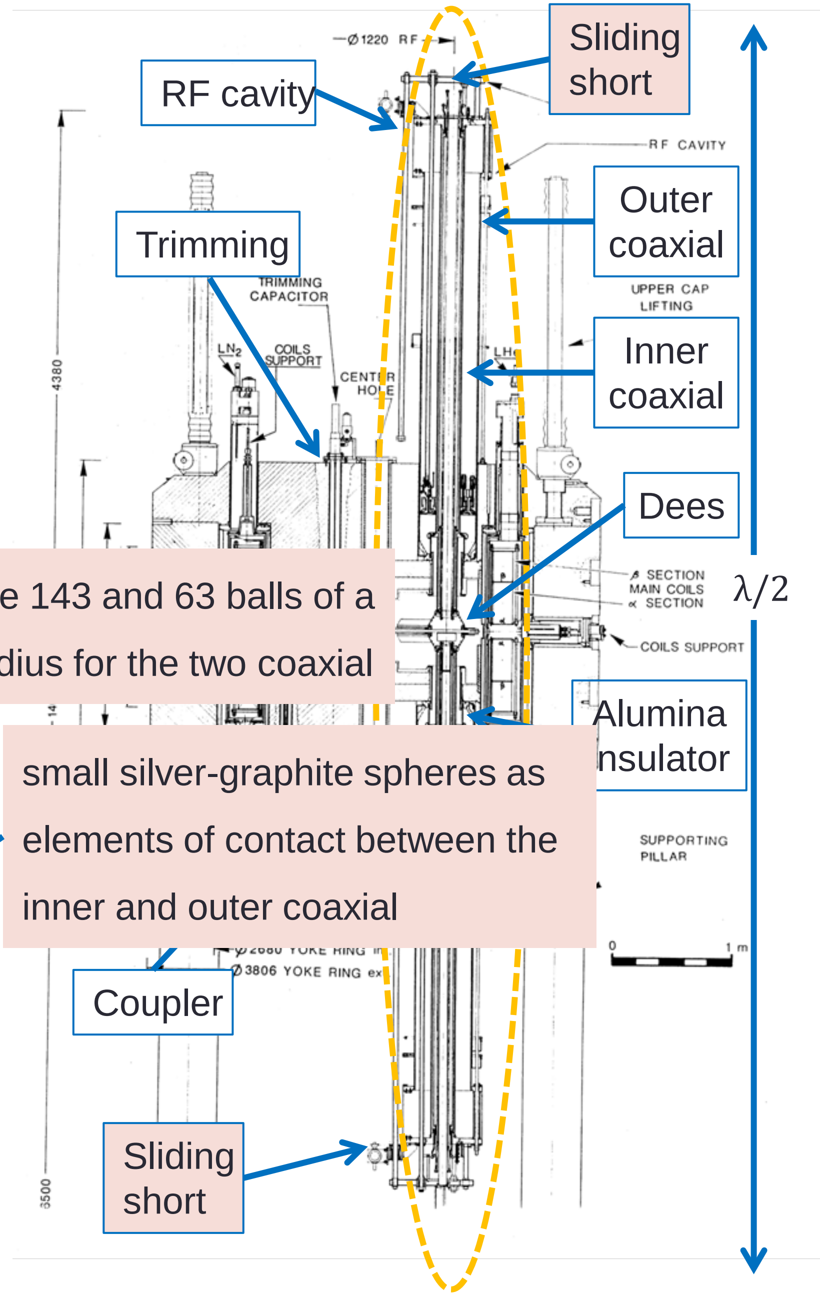
The secondary emission coefficient of the aluminum oxide produced an electrons current between the Dee and the faced copper coupler surface.

At the workshop

Cooling system improved

The sliding short



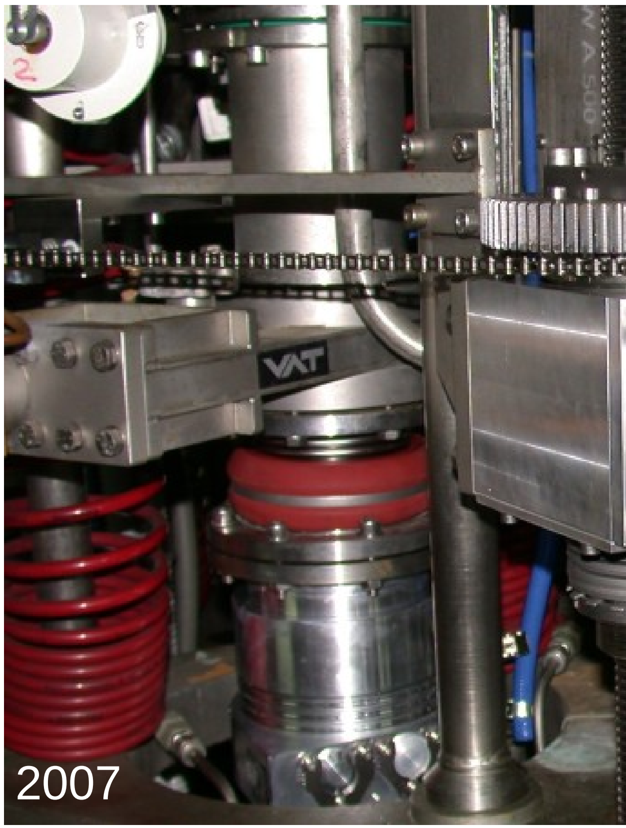


There are 143 and 63 balls of a 5 mm radius for the two coaxial

small silver-graphite spheres as elements of contact between the inner and outer coaxial

The current density at the maximum frequency of 50 MHz can reach 50 A/cm on the short circuit plate

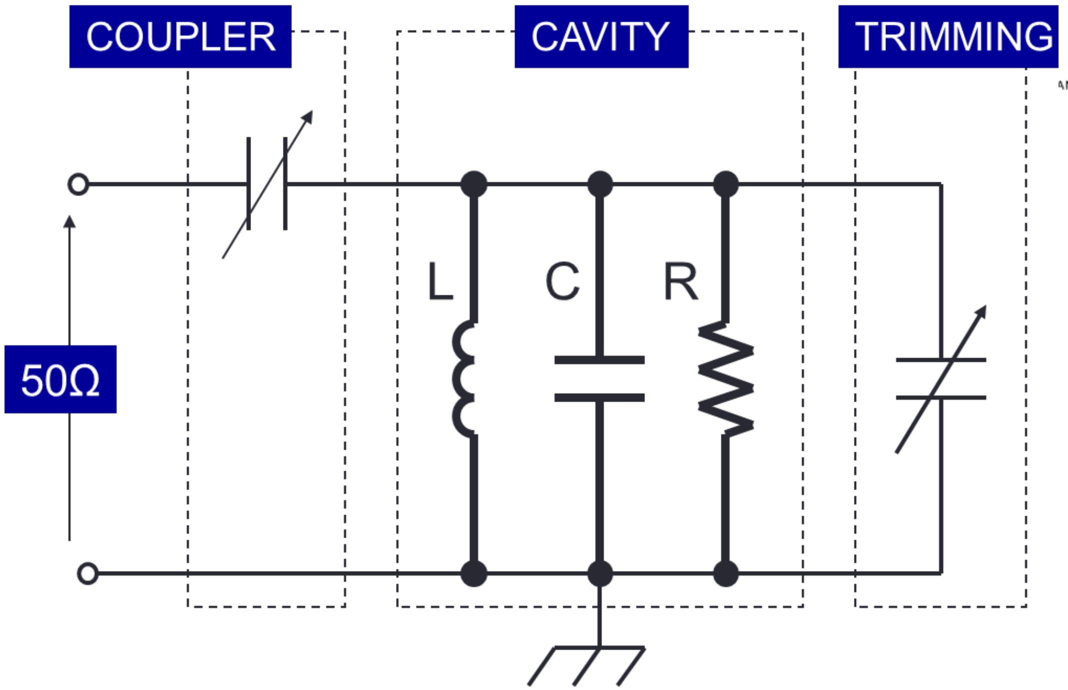
The sliding shorts driving movement



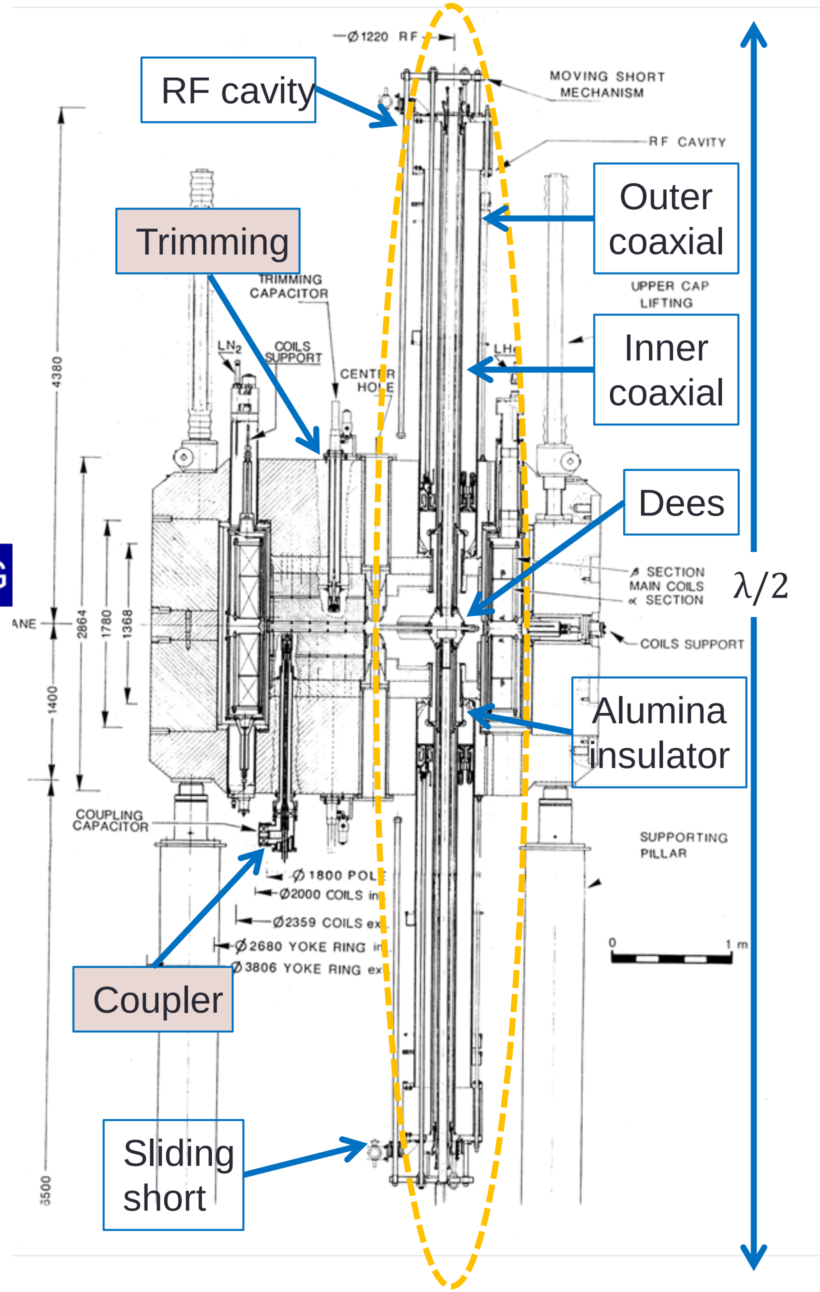
A new control console panel has been developed. It adopts the same software environment of the DDS generator. The console sets and reads the position of the sliding shorts for all the ½λ length of the RF cavities in the frequency range of 15÷48 MHz.

Coupler and trimmer capacitor

AROUND THE RESONANCE FREQUENCY YOU CAN SEE THE CAVITY AS A R-L-C CIRCUIT

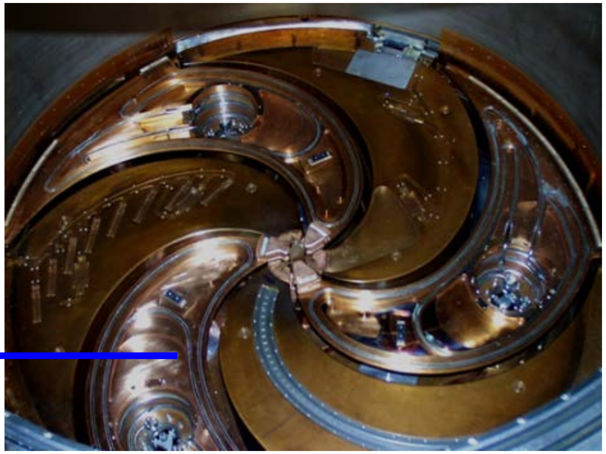


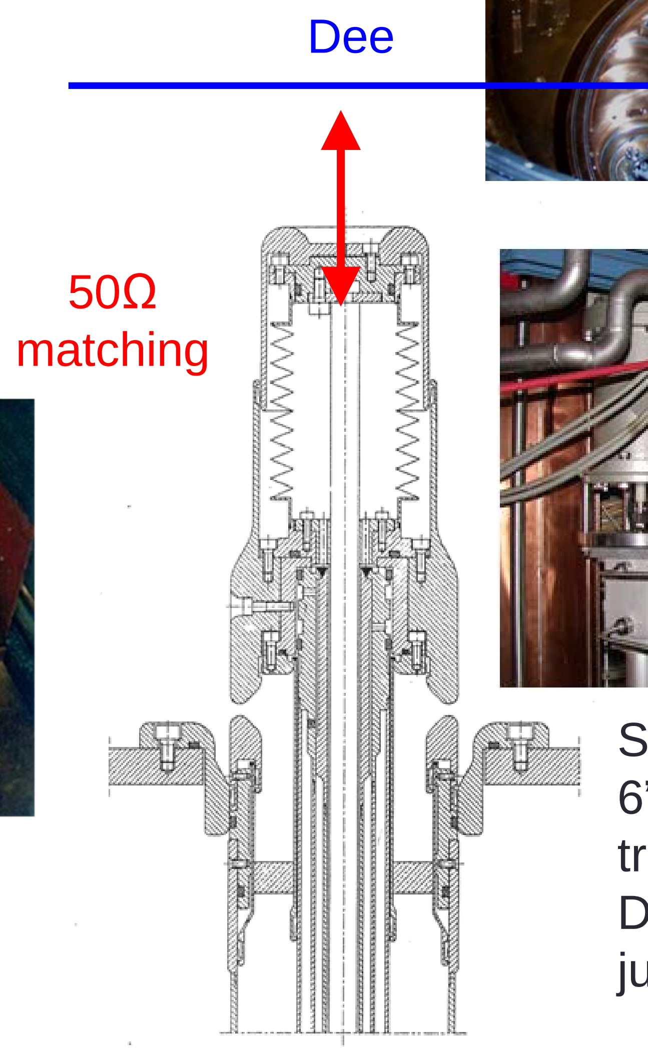
COUPLING-TRIMMING CAPACITOR SCHEMATIC



Coupling capacitor

- relative simple mechanics
- also applicable for tuning control
- high voltage
  - insulator
  - discharge





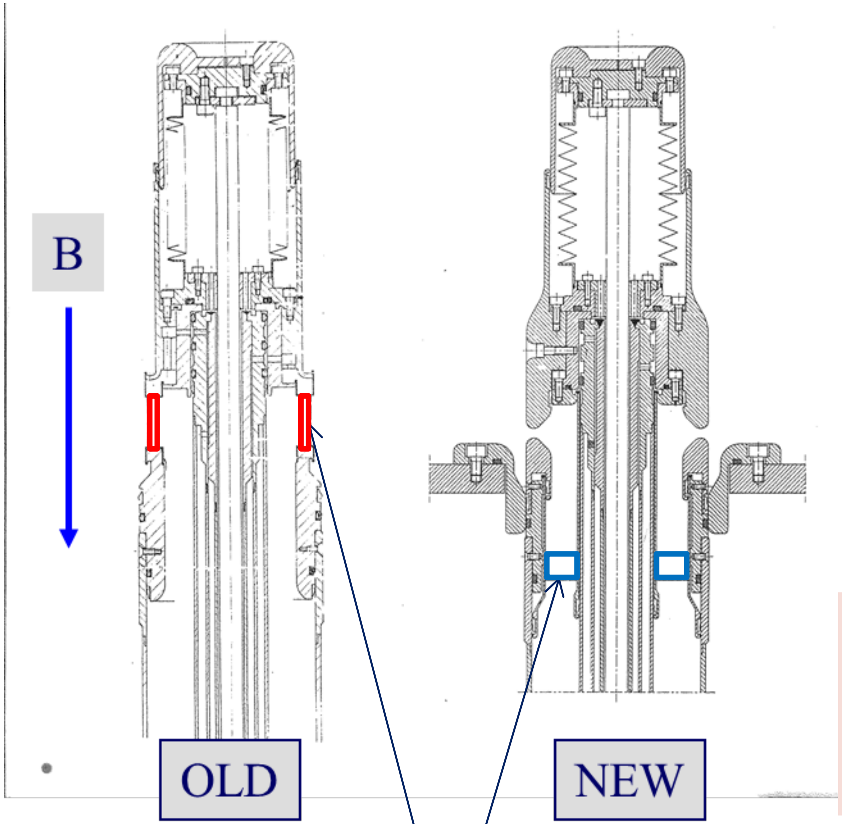
Coupler capacitor under the Dee

The capacitive value is between 2-5 pF and the coupler can be moved in a range or 50 mm.

Standard 6”1/8 coaxial rigid transmission line, Directional coupler just before the coupler

Something to strongly avoid

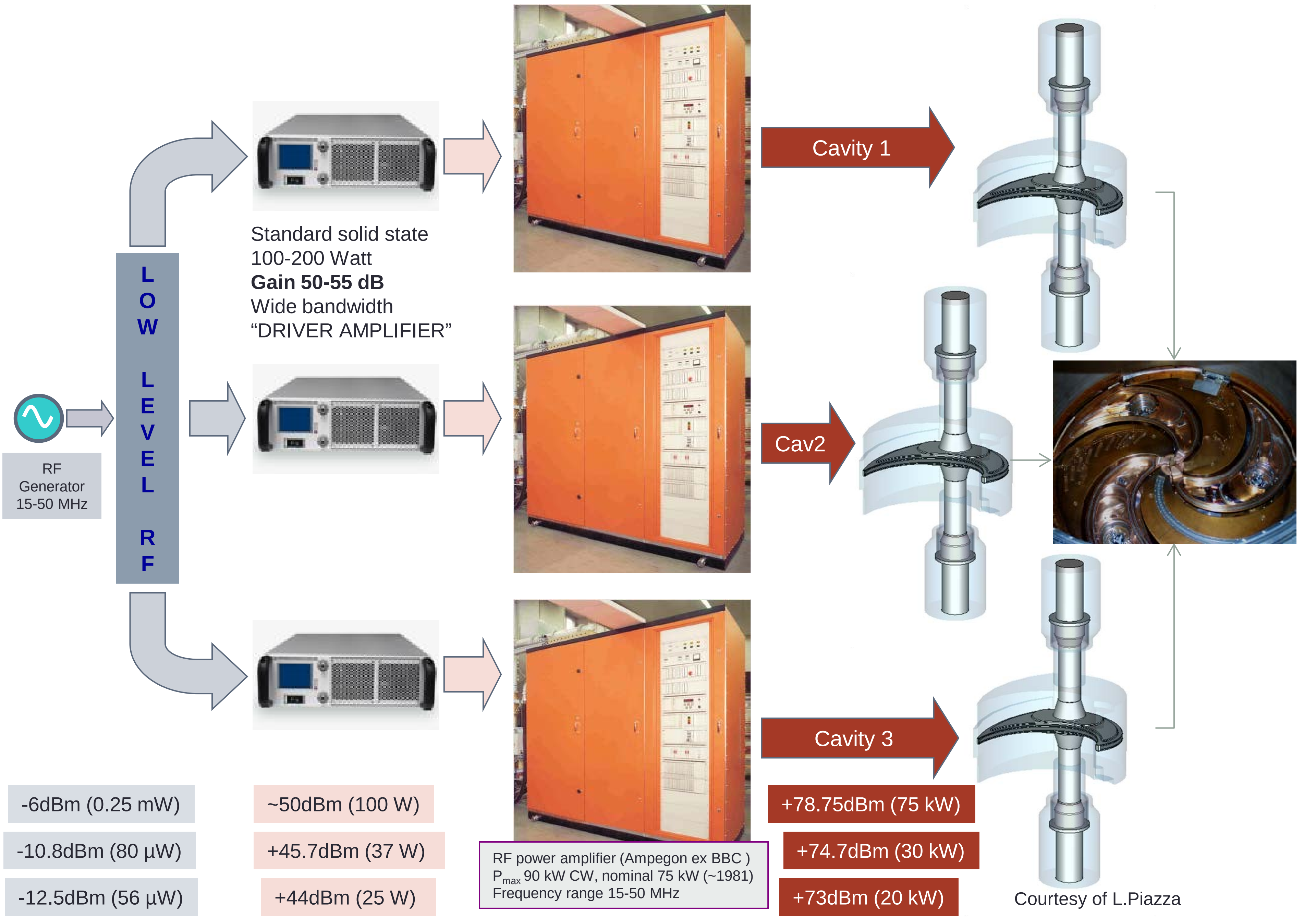
avoid ceramic insulator parallel to magnetic field



Ceramic feed-through

We adopted a disc shape insulator to replace the cylindrical one (1995)

The reason was a resonant discharge across the cylindrical ceramic insulator. The discharge was strongly focalized by the strong intensity of the magnetic field


LOW LEVEL RF
RF Generator 15-50 MHz
Standard solid state
100-200 Watt
Gain 50-55 dB
Wide bandwidth
“DRIVER AMPLIFIER”
Cavity 1
Cav2
Cavity 3
-6dBm (0.25 mW)
-10.8dBm (80 µW)
-12.5dBm (56 µW)
~50dBm (100 W)
+45.7dBm (37 W)
+44dBm (25 W)
RF power amplifier (Ampegon ex BBC)
Pmax 90 kW CW, nominal 75 kW (~1981)
Frequency range 15-50 MHz
+78.75dBm (75 kW)
+74.7dBm (30 kW)
+73dBm (20 kW)
Courtesy of L.Piazza

Input filter sta
• wide band
• adapts from
tetrode and D
•The RF powe
dissipated on
•No tuning is r

The 2nd stage (T2=4CW100000): **common-grid configuration**, high isolation between the in/out sections. Filament input. Water cooled. The load is a ¼ λ cavity plus a capacity.

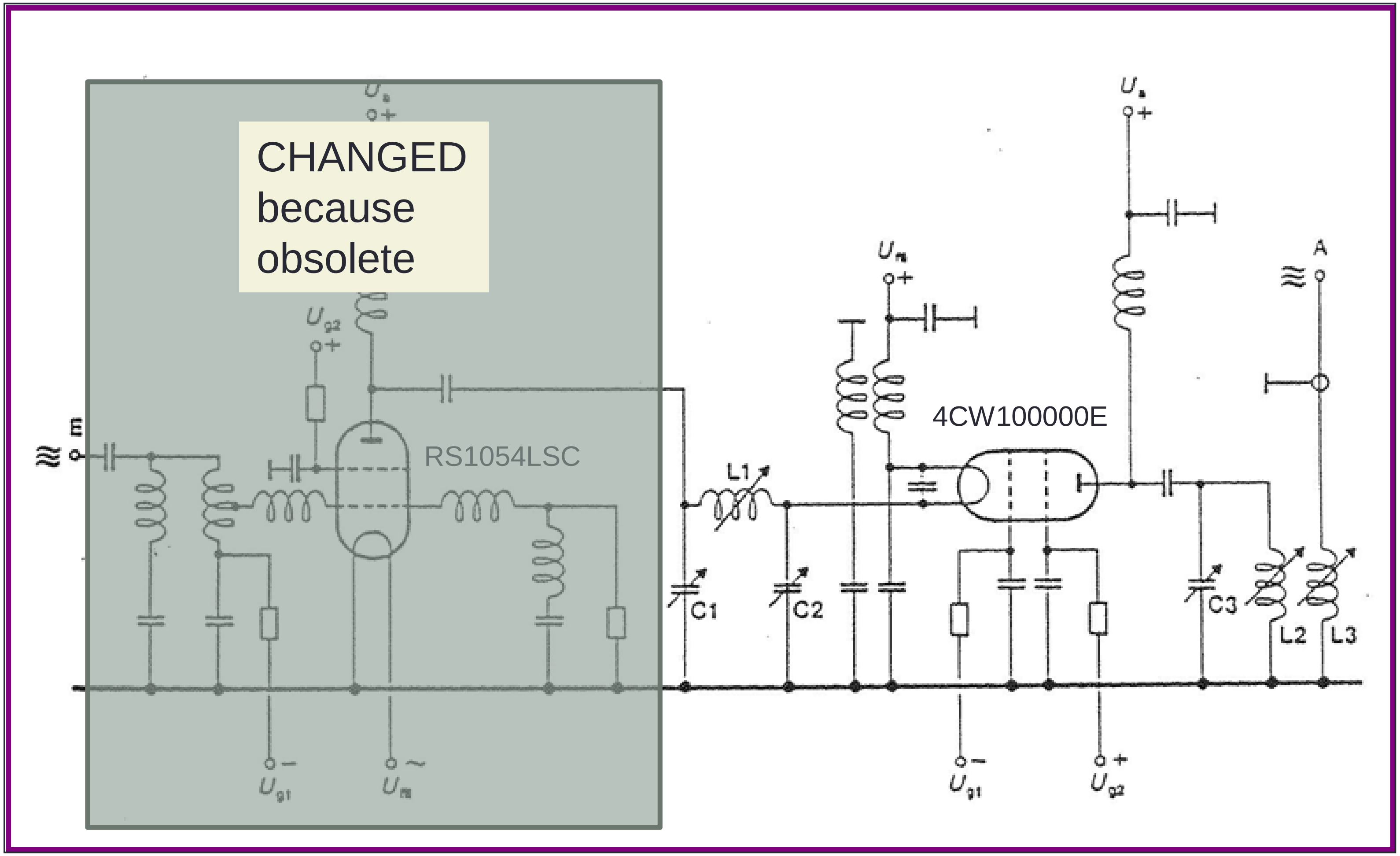
e two
load for the
the input
tage at the
ponents,
e are

stage is a **ground-cathode**
ration. In general this
ration is very reliable,
very few technical
ns and a considerably low
r of components.
ntrol input.
Class AB.
Forced air cooled.
P_{OUT} 5 kW
T1 THALES RS1054L

INPUT FILTER

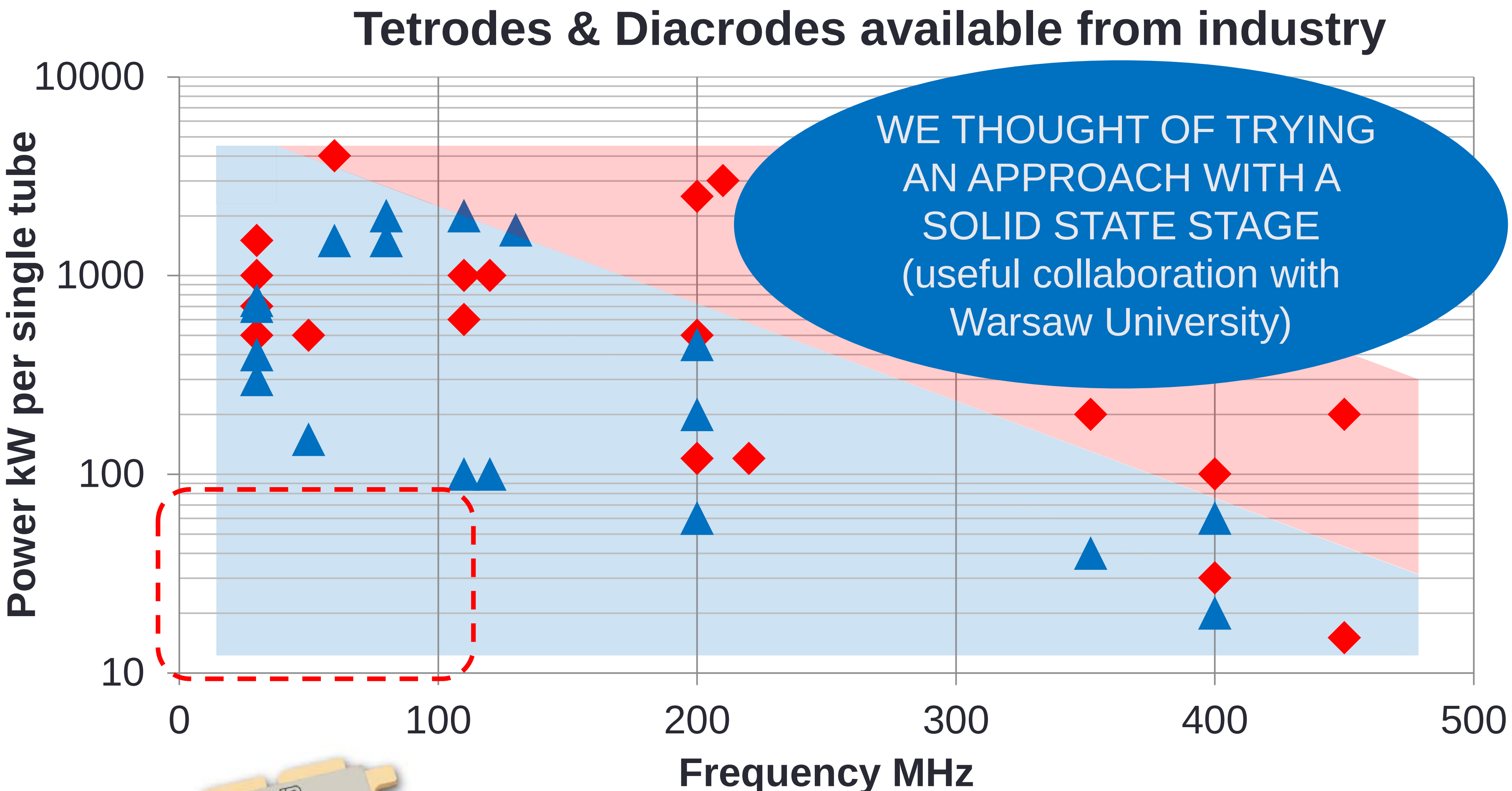
1st stage (THALES RS1054LSC)

2nd stage (CPI-4CW100000E)


CHANGED
because
obsolete
RS1054LSC
4CW100000E
E
A
L1
L2
L3
C1
C2
C3

Frequency & Power range of tetrodes

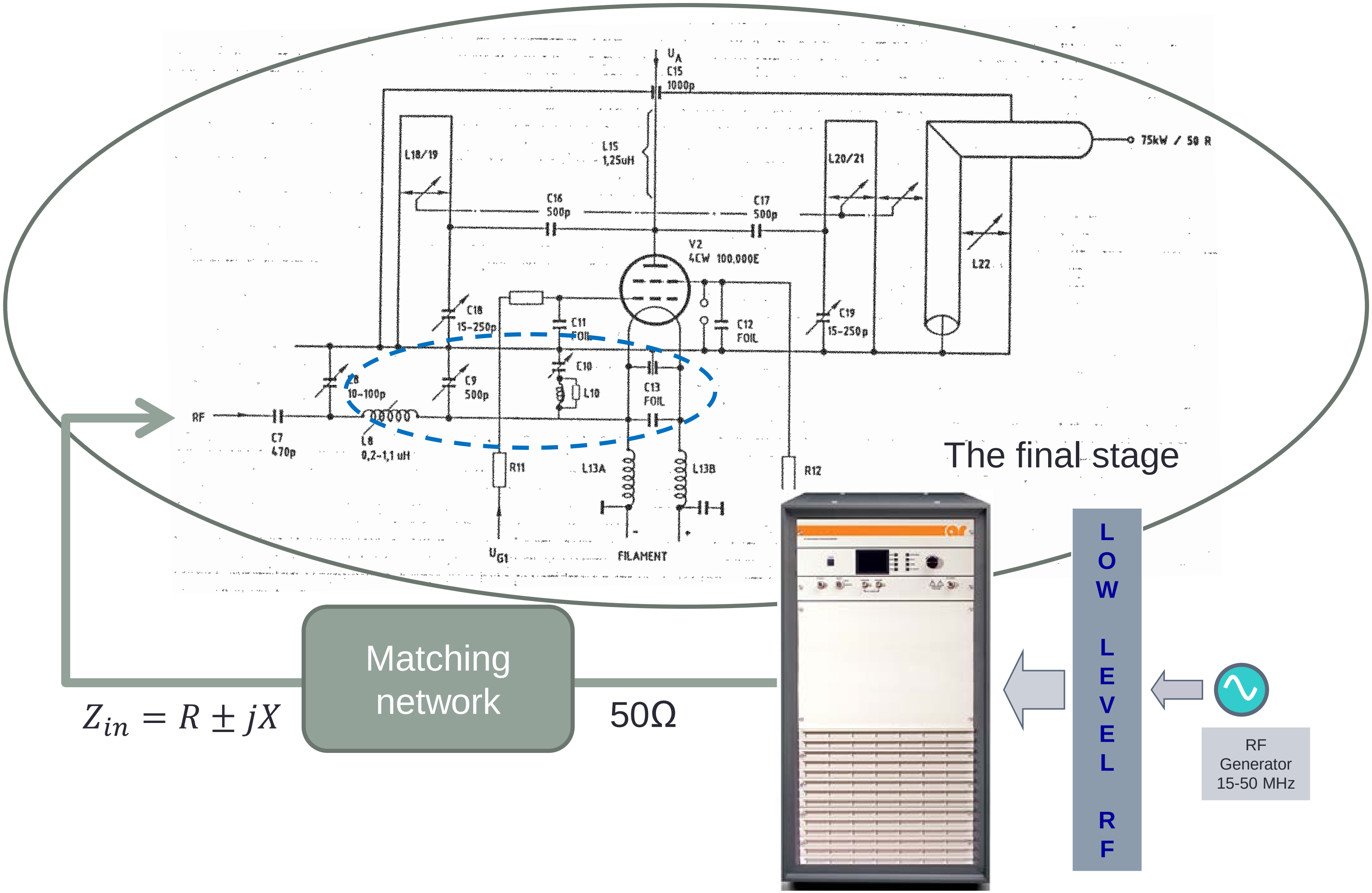
In the meanwhile further news coming from the market …

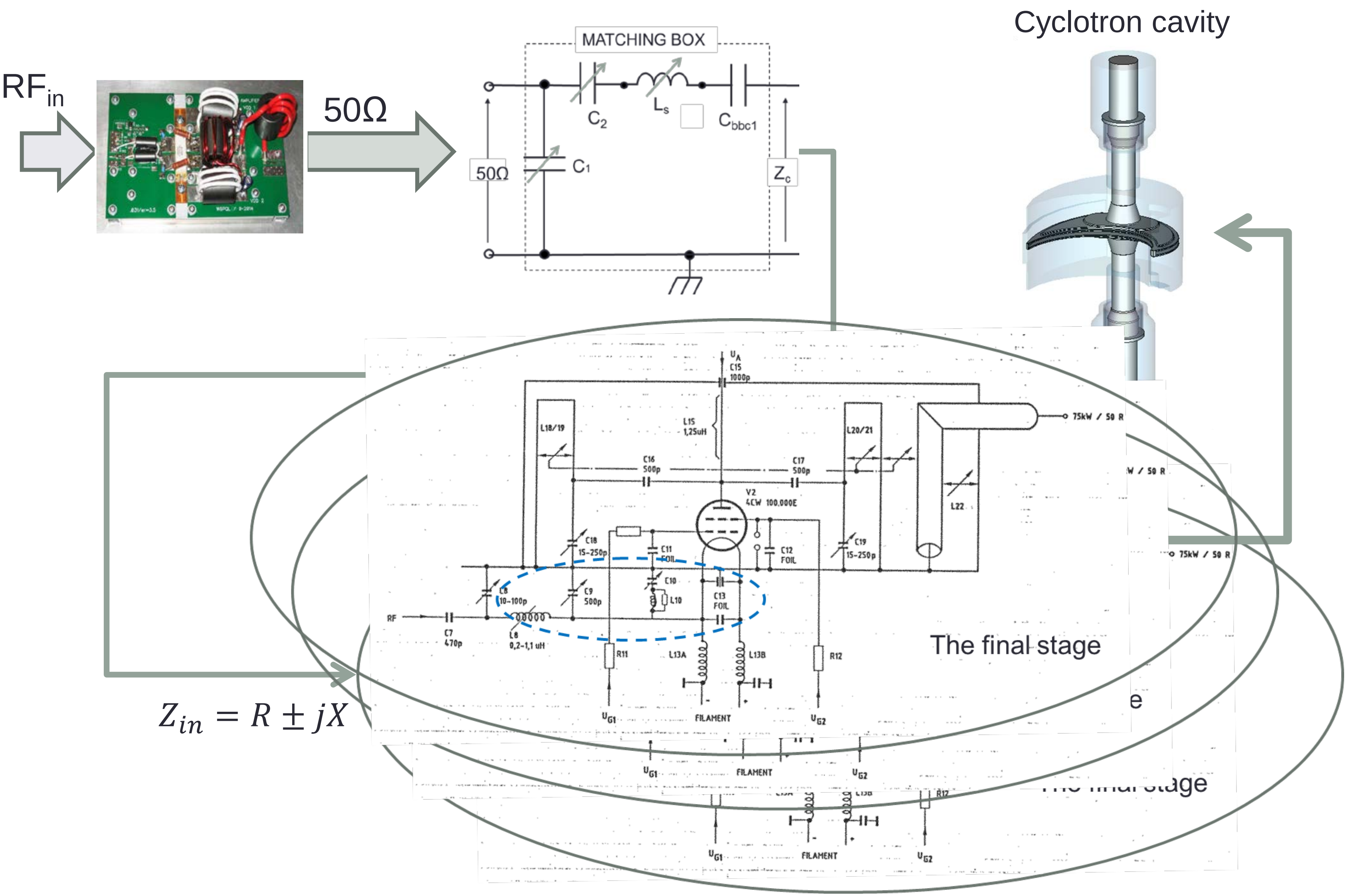


LDMOS Transistor
>1 kW, 2-600 MHz

Courtesy of Eric Montesinos, CERN-RF

Matching the new solid state driver with the 2nd stage




RF$_{in}$
50Ω
MATCHING BOX
C$_2$
L$_s$
C$_{bbc1}$
C$_1$
50Ω
Z$_c$
Cyclotron cavity
U$_A$
C15 1000p
L15 1,25uH
L18/19
L20/21
C16 500p
C17 500p
V2 4CW 100,000E
75kW / 50 R
L22
C18 15-250p
C19 15-250p
C11 FOIL
C12 FOIL
C10
L10
C13 FOIL
C8 10-100p
C9 500p
RF
C7 470p
L8 0,2-1,1 uH
R11
L13A
L13B
R12
U$_{G1}$
FILAMENT
U$_{G2}$
The final stage
$Z_{in} = R \pm jX$

DRIVER BASED ON NEW LDMOS FREESCALE

We got a pre assembled board and made a driver amplifier…

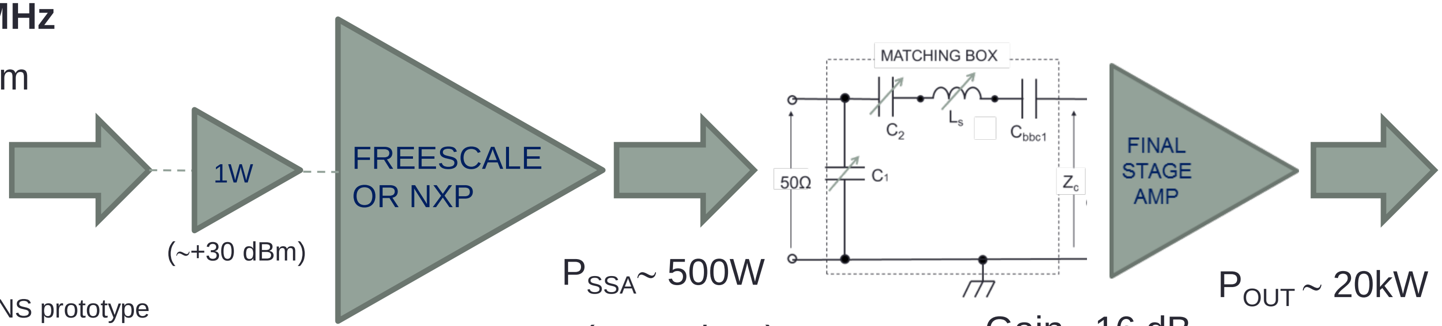
33.74 MHz
29.835 MHz
16.35 MHz
39.3112 MHz

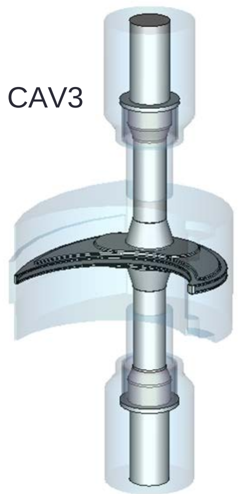
LDMOS Transistor
>1 kW, 2-600 MHz

CAV3

P_{IN}~ 0 dBm

From LLRF





(~+30 dBm)

P_{SSA}~ 500W

(~+57 dBm)

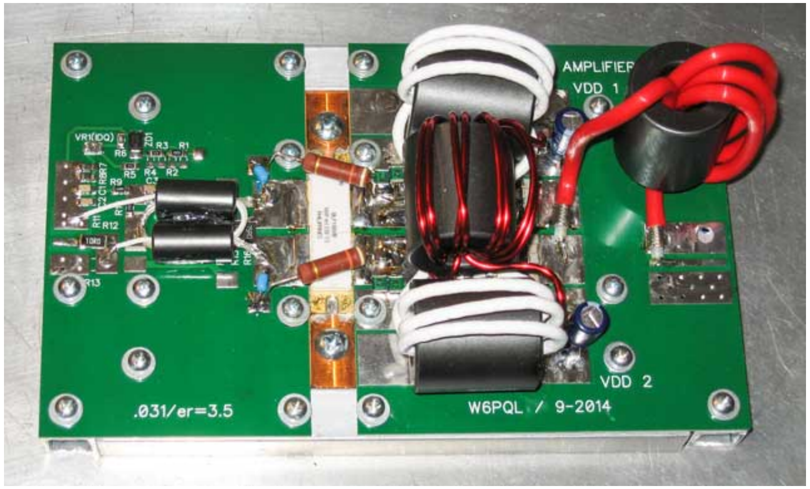
Gain ~16 dB

P_{OUT} ~ 20kW

INFN/LNS prototype

1 kW, 1.8 - 54 MHz

Gain 27 dB (average)



Output Power ≥ 1kW

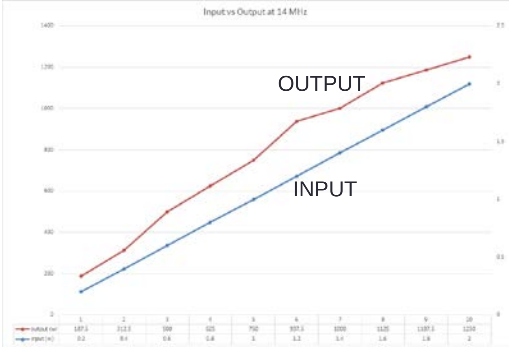
Flatness ± 1.5 dB

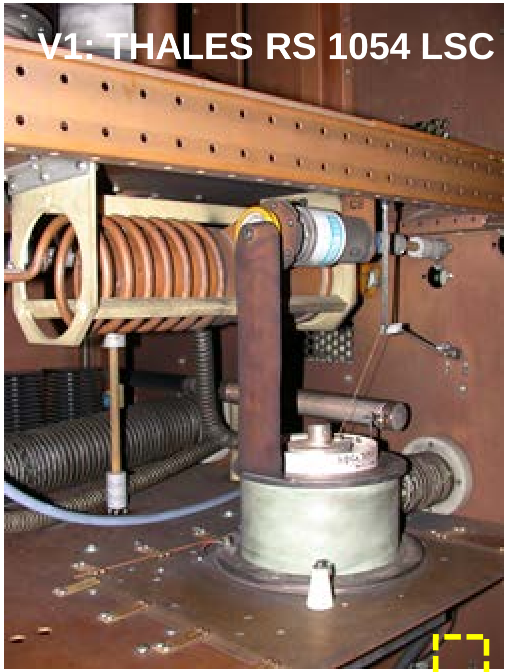
Gain ~ 27 dB

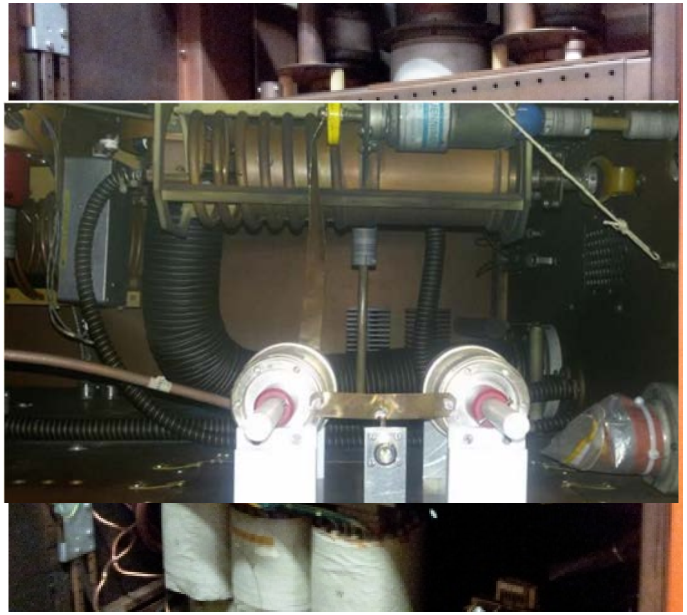
Mismatch max tested 2:1

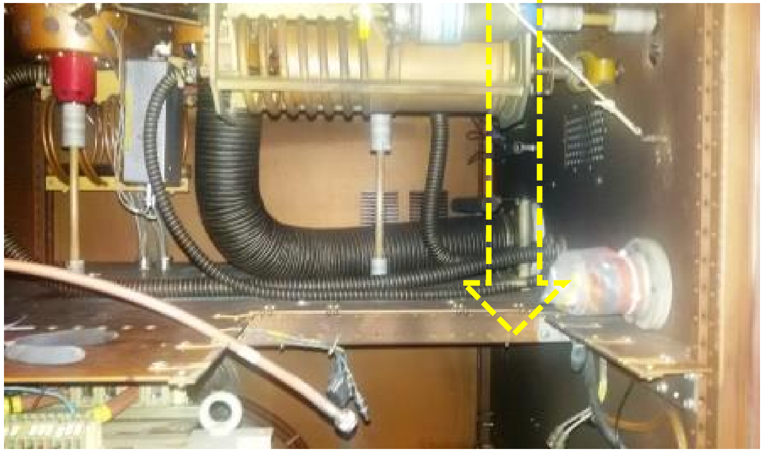
Frequency range 1.8 - 54 MHz

MRFE6VP61K25HR6 (FREESCALE)









The matching box already installed instead of the 1st stage RS1054LSC in one of the 3 amplifiers

RF power switch

A USEFUL TOOL

Courtesy of L.Piazza

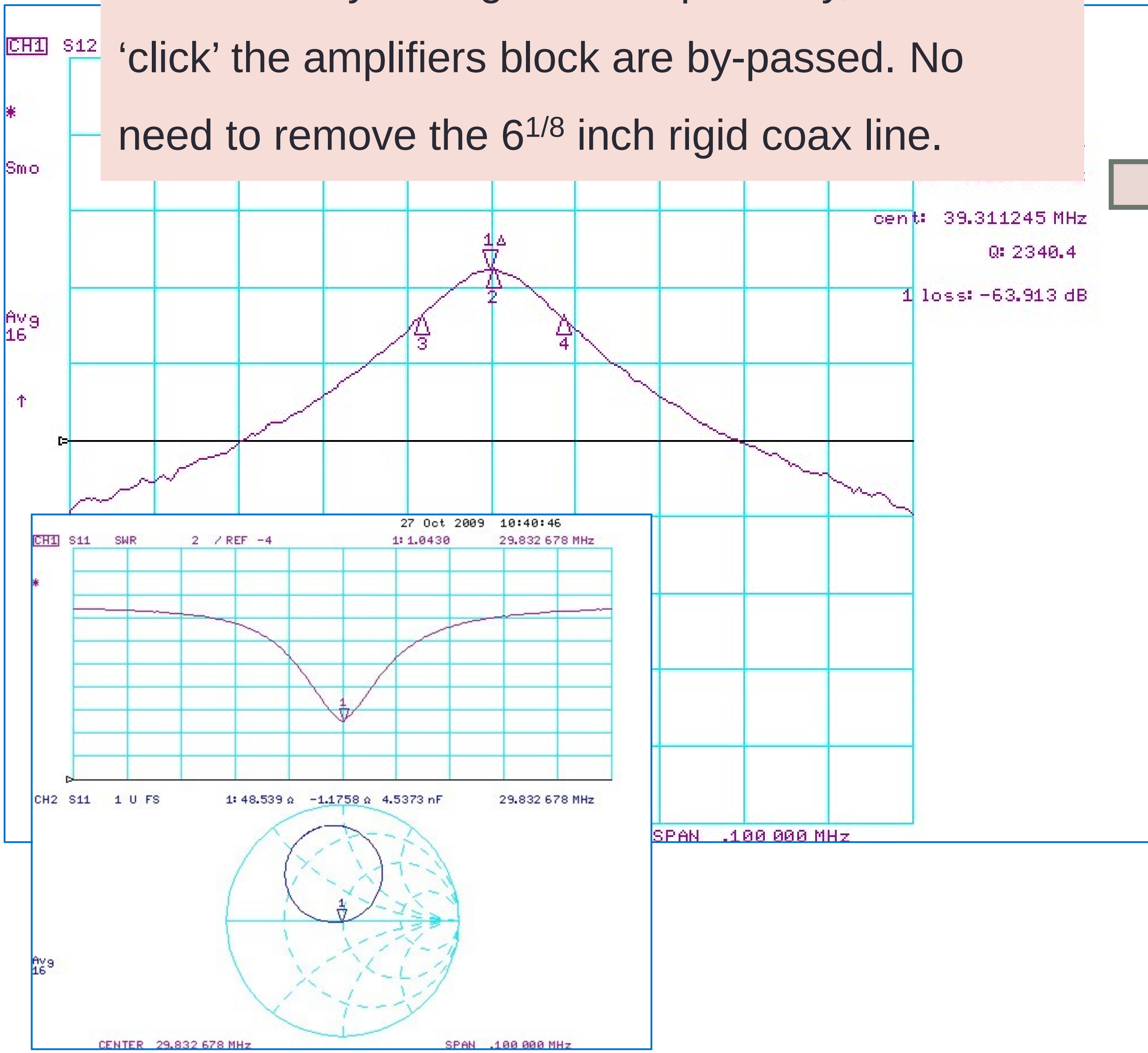
Directional coupler

Power switch

RF amplifier

Dummy load

The RF instruments can be directly connected to the RF cavity through the coupler only, with one ‘click’ the amplifiers block are by-passed. No need to remove the $6^{1/8}$ inch rigid coax line.

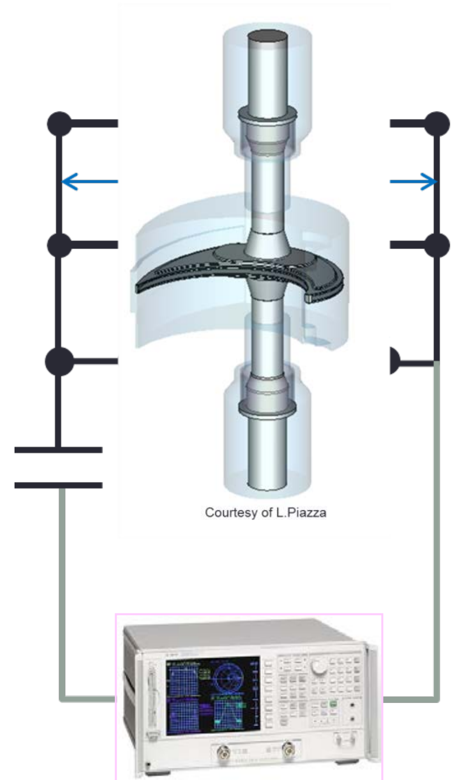


$$Q = f_0/\Delta f$$

$$f = 39.3112\ MHz$$

$$\Delta f \cong 16.8\ kHz$$

$$Q_{loaded} = 2340$$



LLRF (low level RF control system)

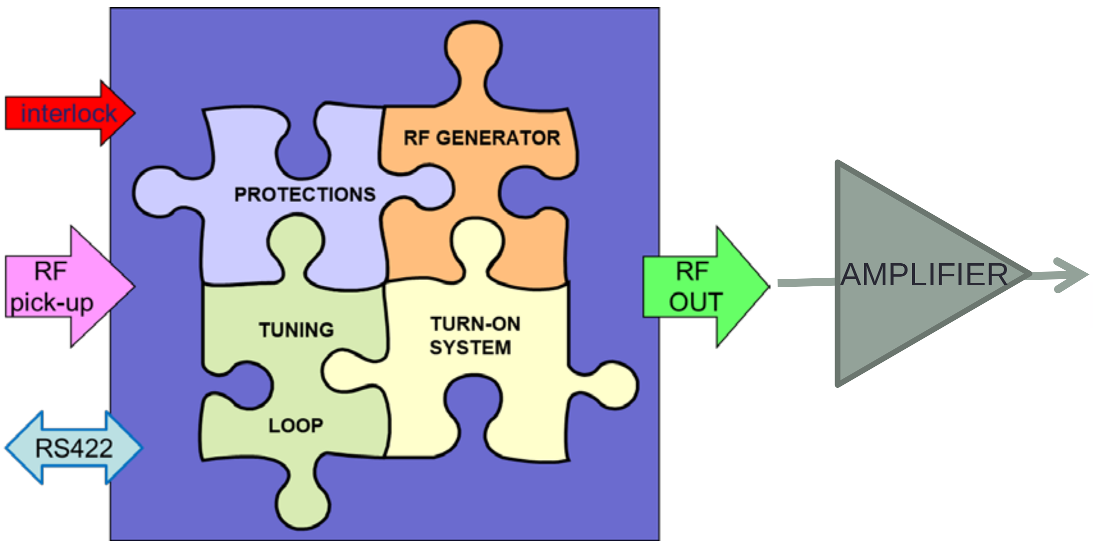
and

the digital LLRF-Box

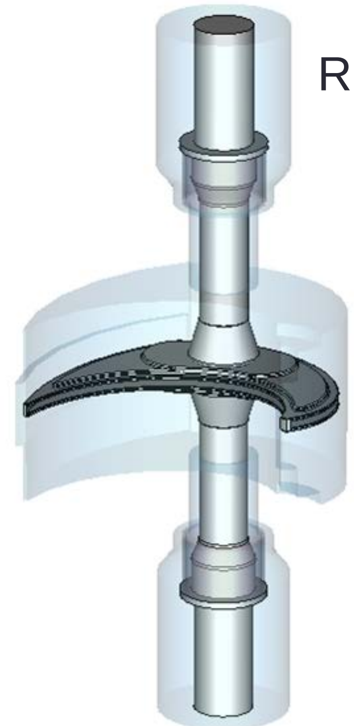
- Protects the system from sparks, multipactoring, reflected power
- *Vacuum level, water cooling, temperature*
- Turns the system on/off
- Change and check the tuning at the resonance frequency
- Stabilize the accelerating voltage in amplitude and phase

In one single compact unit: The LLRF-Box

LLRF-Box



RF-Cavity



Courtesy of L. Piazza

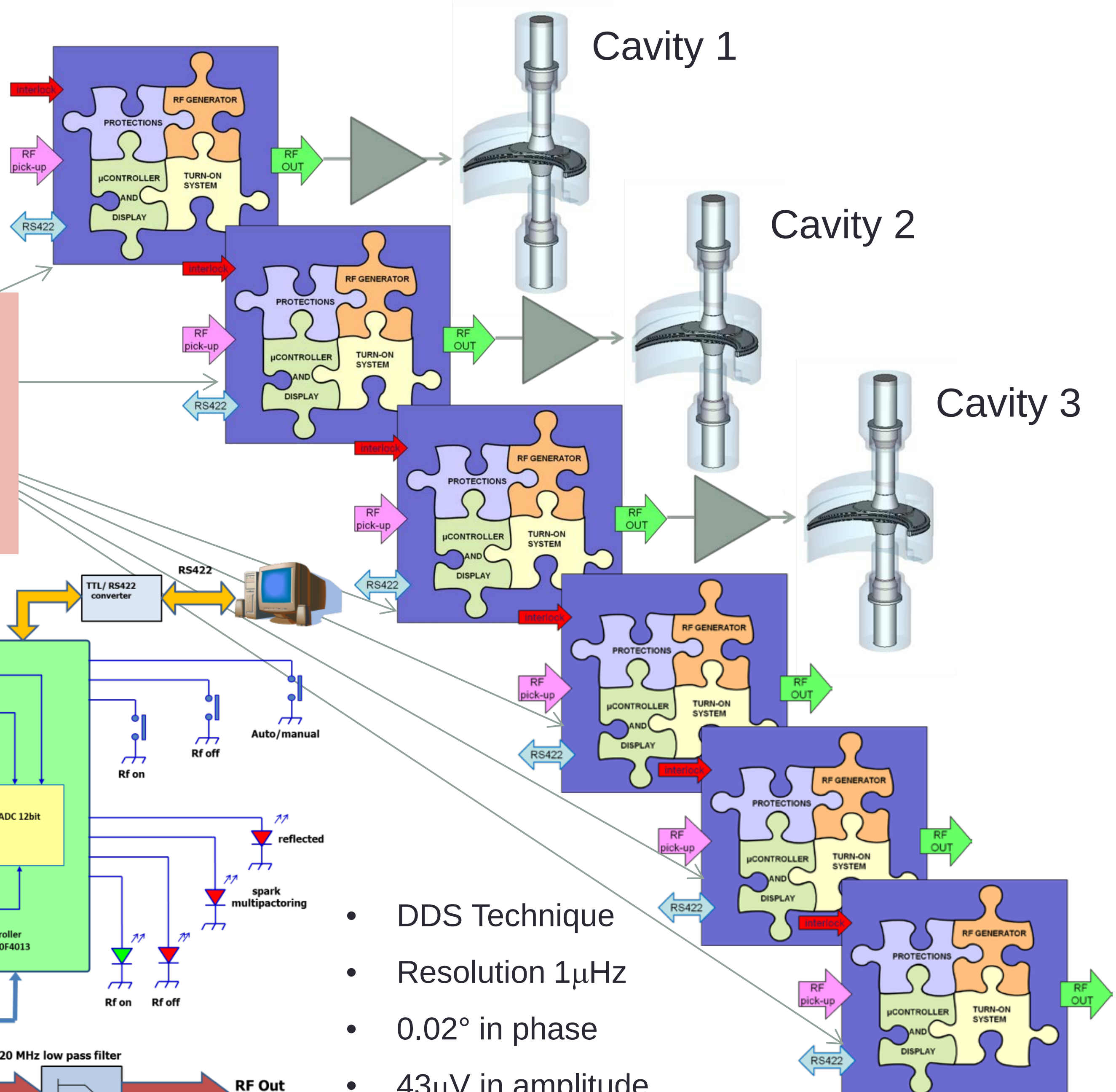
One single compact rack includes:

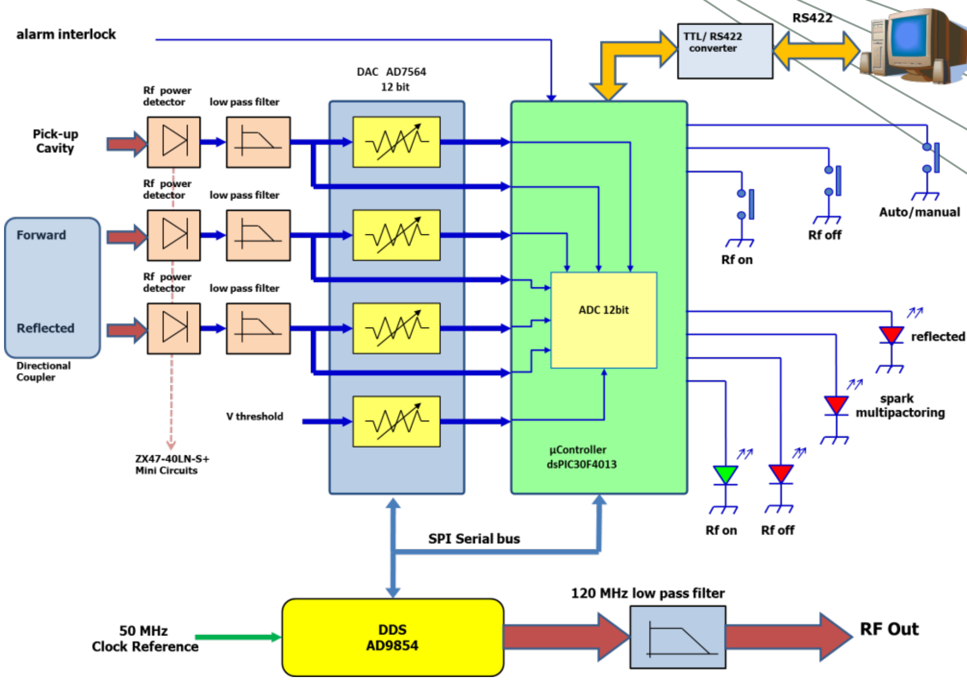
- Direct Digital Synthesizer (RF-generator);
- turn-on;
- Protection devices (sparks, reflected wave, interlocks);
- Automatic Tuning loop.

The system synthesizes a highly stable RF signal up to 120 MHz, turns the power on in the RF cavities through a step-ramp modulator, and protects the RF system against mismatching, sparks and multipactoring

50 MHz Ultra low noise (-160 dBc/Hz@ 10kHz) high precision oscillator.

The clock **synchronizes** all the LLRF-Boxes necessary for the three RF cavities of the cyclotron plus the pulsing systems (buncher, choppers, external reference).

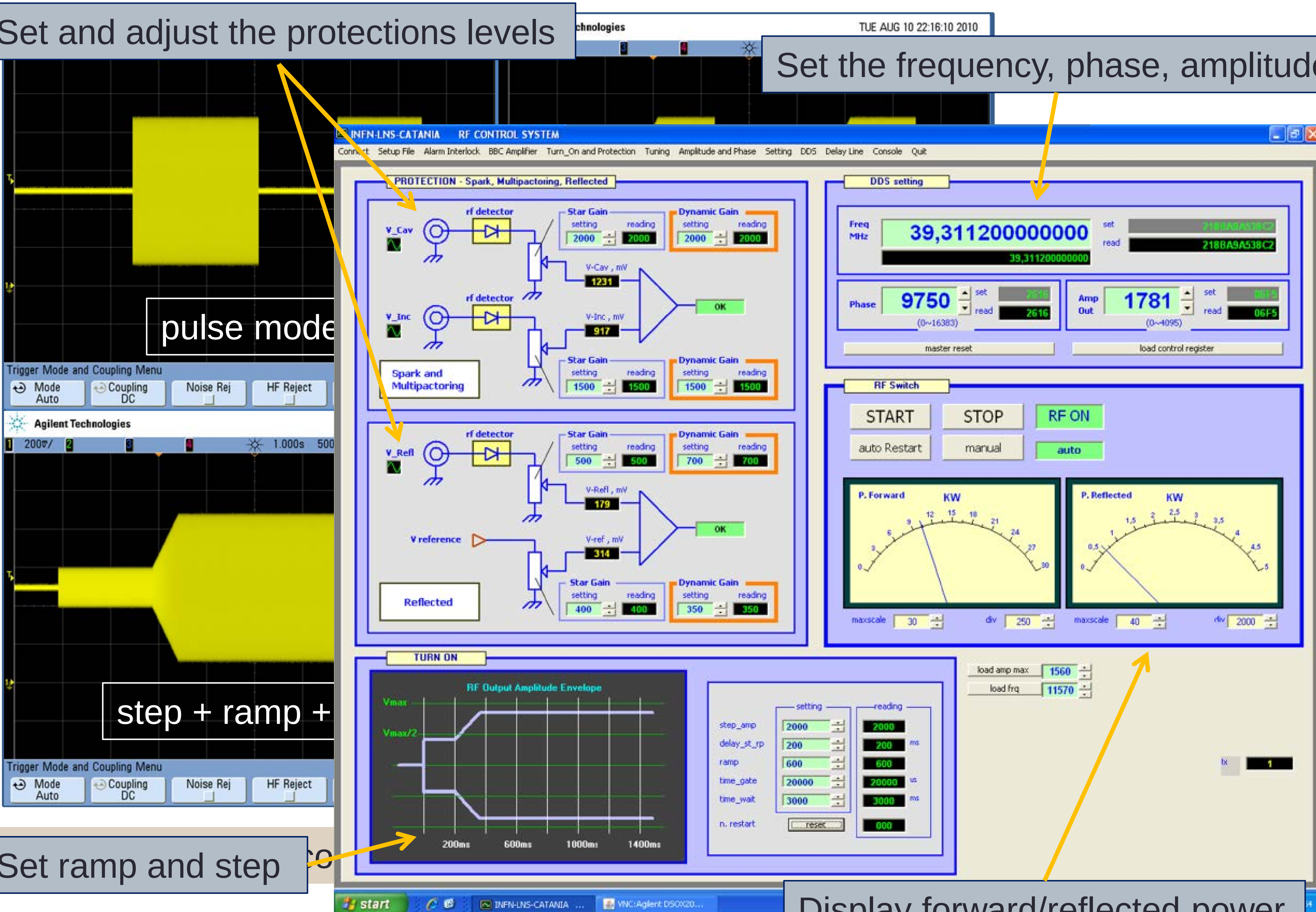




- DDS Technique
- Resolution 1μHz
- 0.02° in phase
- 43μV in amplitude

Set and adjust the protections levels

Set the frequency, phase, amplitude



Set ramp and step

Display forward/reflected power

Phase and amplitude stability

$$\Delta E = 2qV_D(\sin \varphi)$$

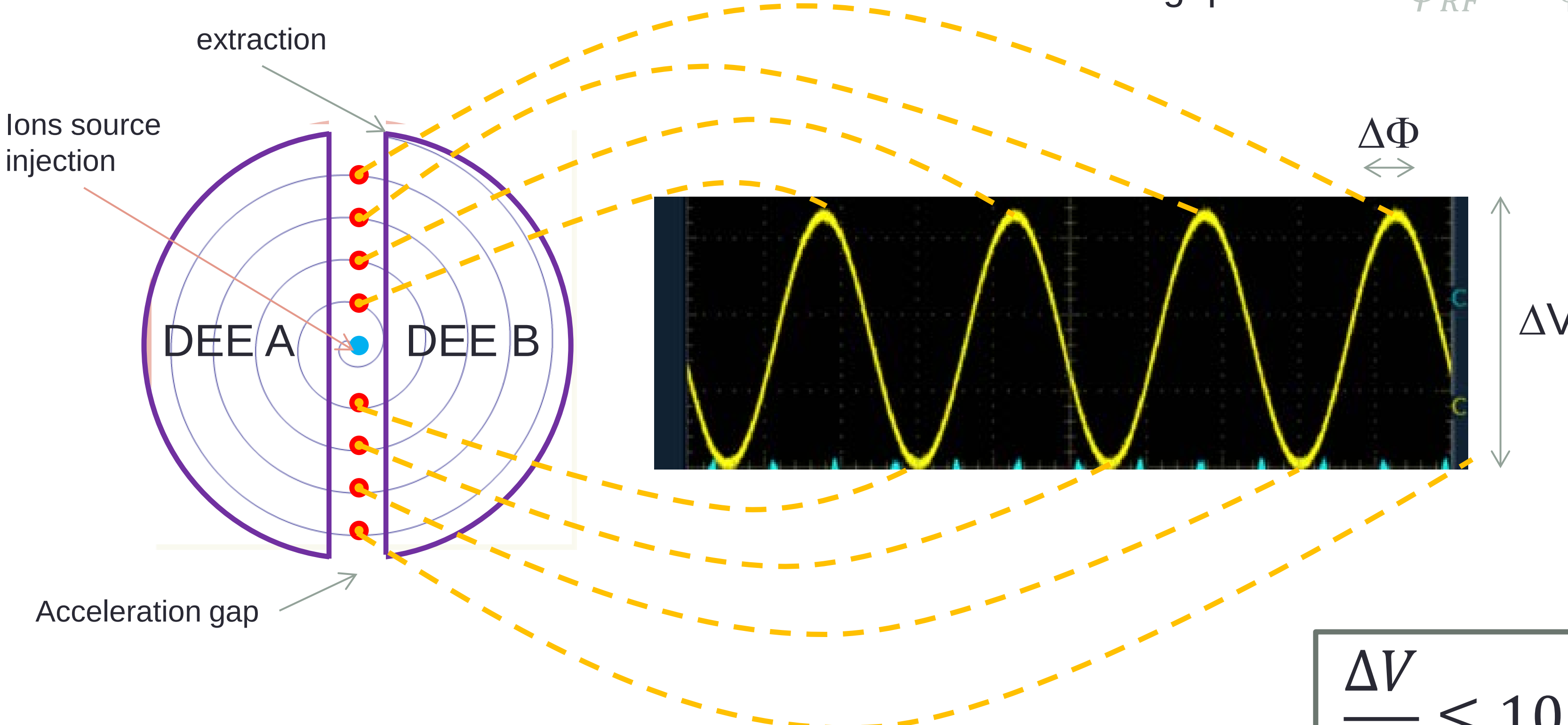
Maximum energy gain for ions each time crosses the acceleration gap

$$\varphi = \varphi_{ion} - \varphi_{RF}$$

$$\varphi_{RF} = \psi$$

$$f = \frac{qB}{2\pi m}$$

$$\omega = 2\pi f$$



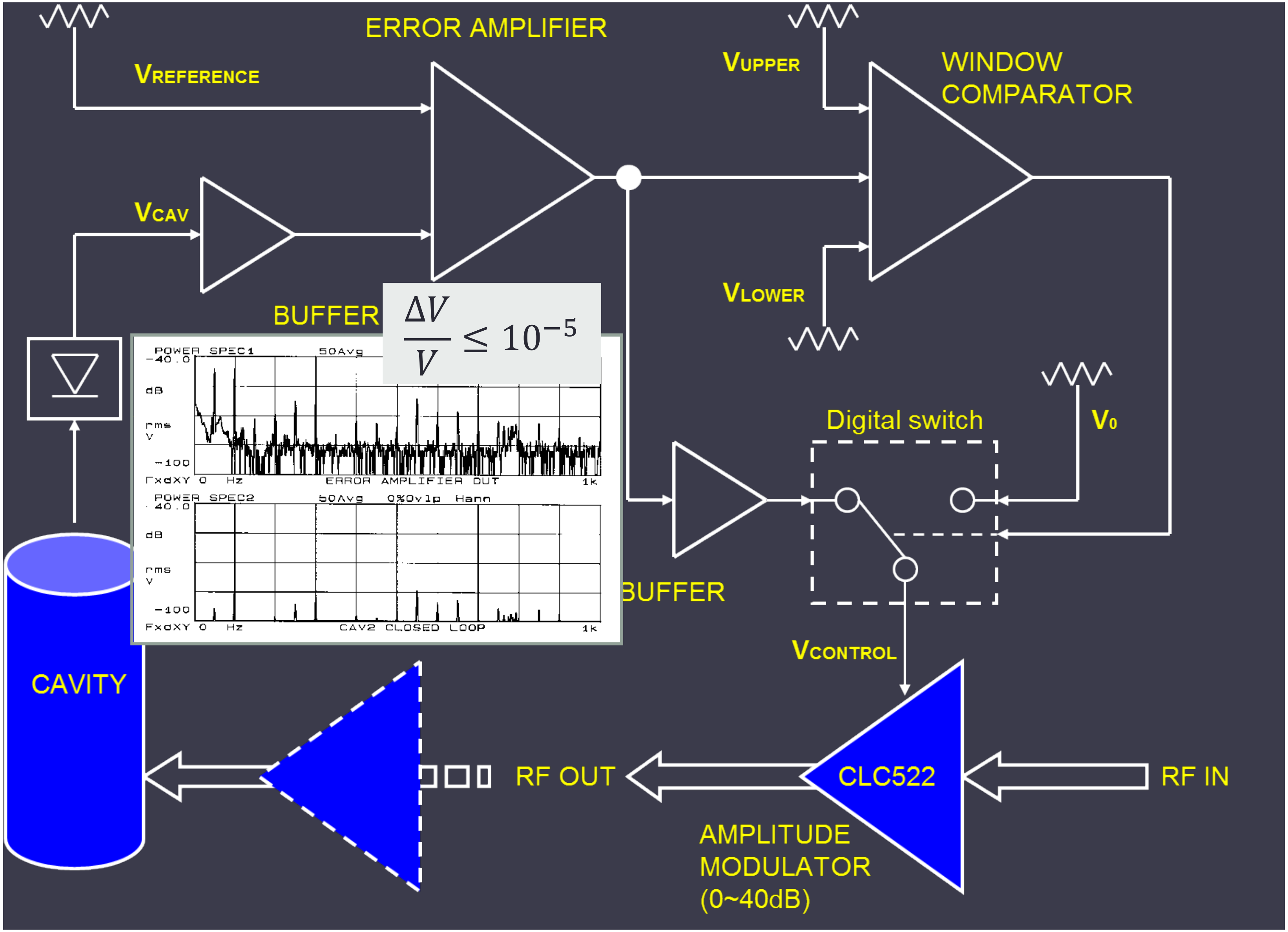
$$V_D(t) = V_D \cos(\omega_{RF} t + \square)$$ Accelerating voltage

$$\frac{\Delta E}{E} = 10^{-3}\ energy\ stability\ of\ accelerating\ beam$$

$$\frac{\Delta V}{V} \leq 10^{-5}$$

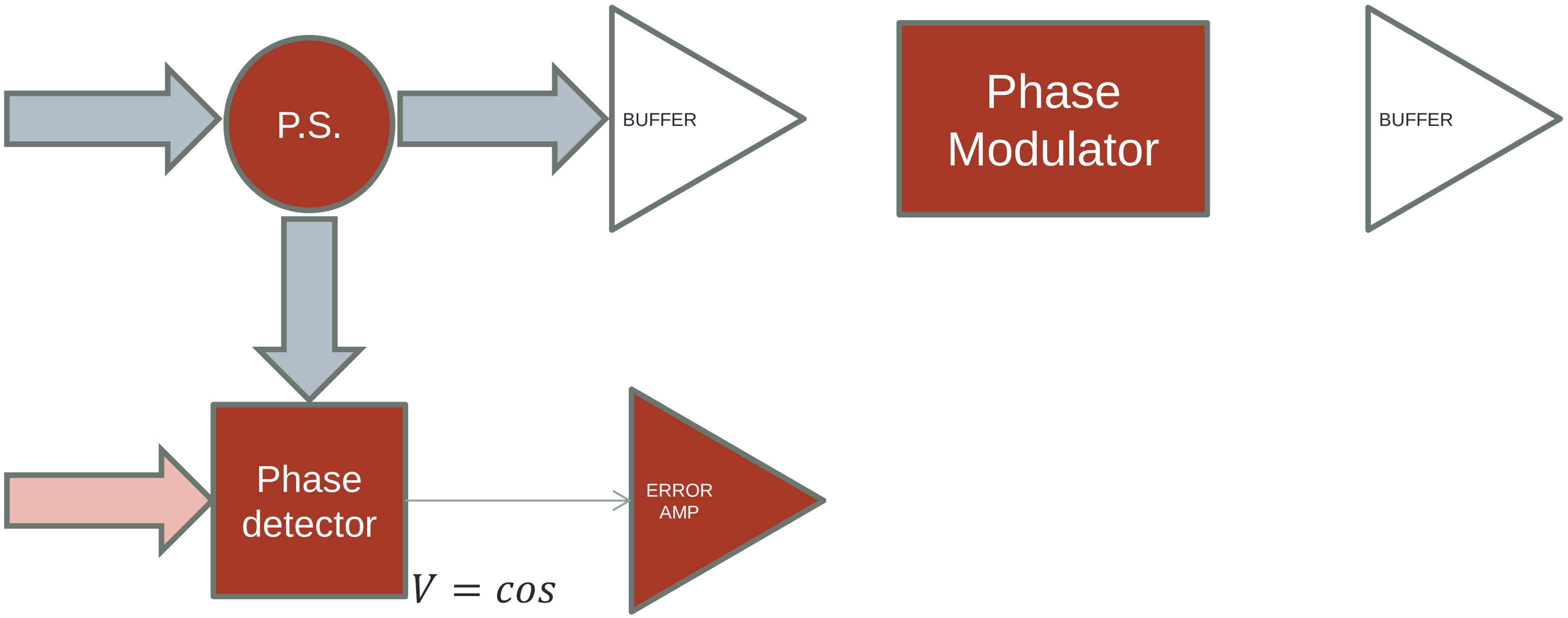
$$\Delta\Phi = \pm 0.1°$$

Amplitude stabilization loop

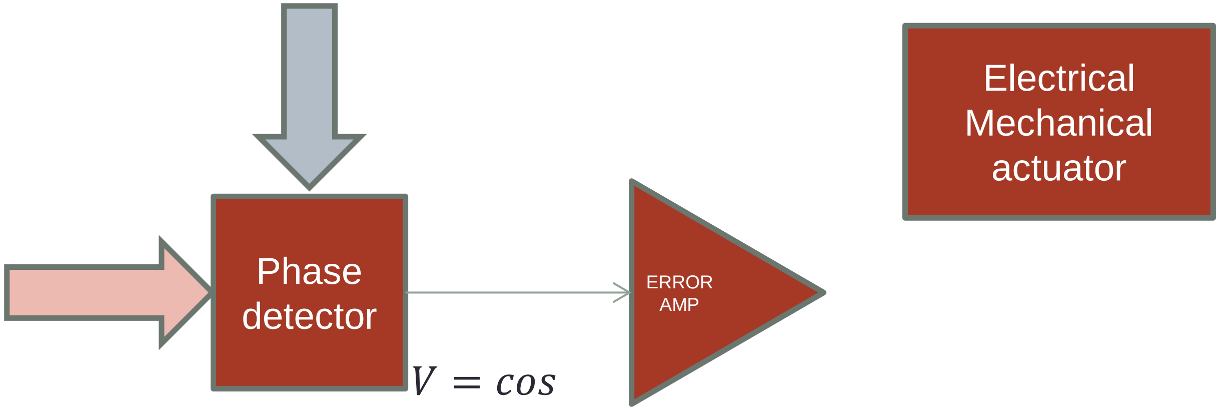


$$\frac{\Delta V}{V} \leq 10^{-5}$$

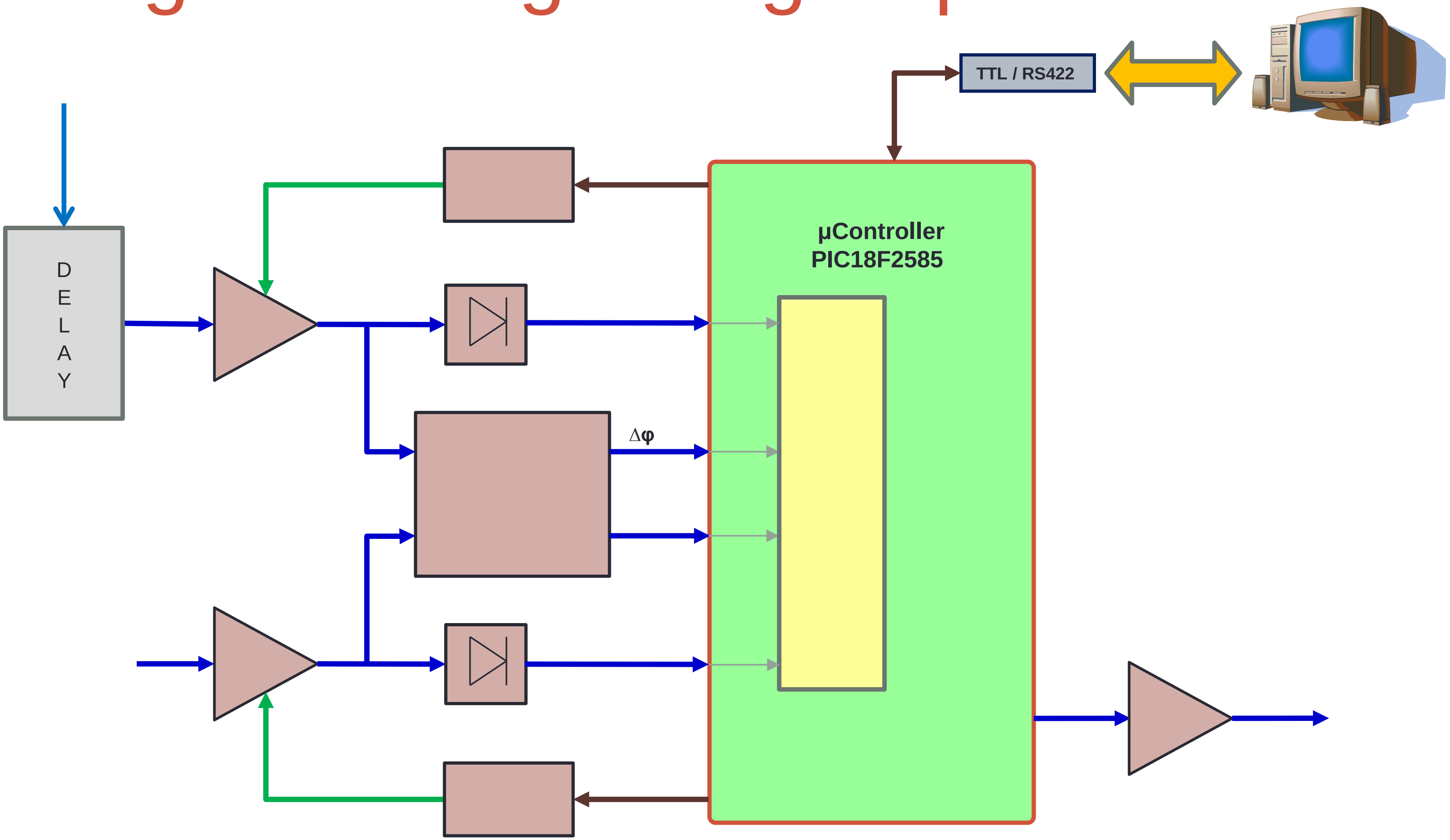
Phase stabilization loop



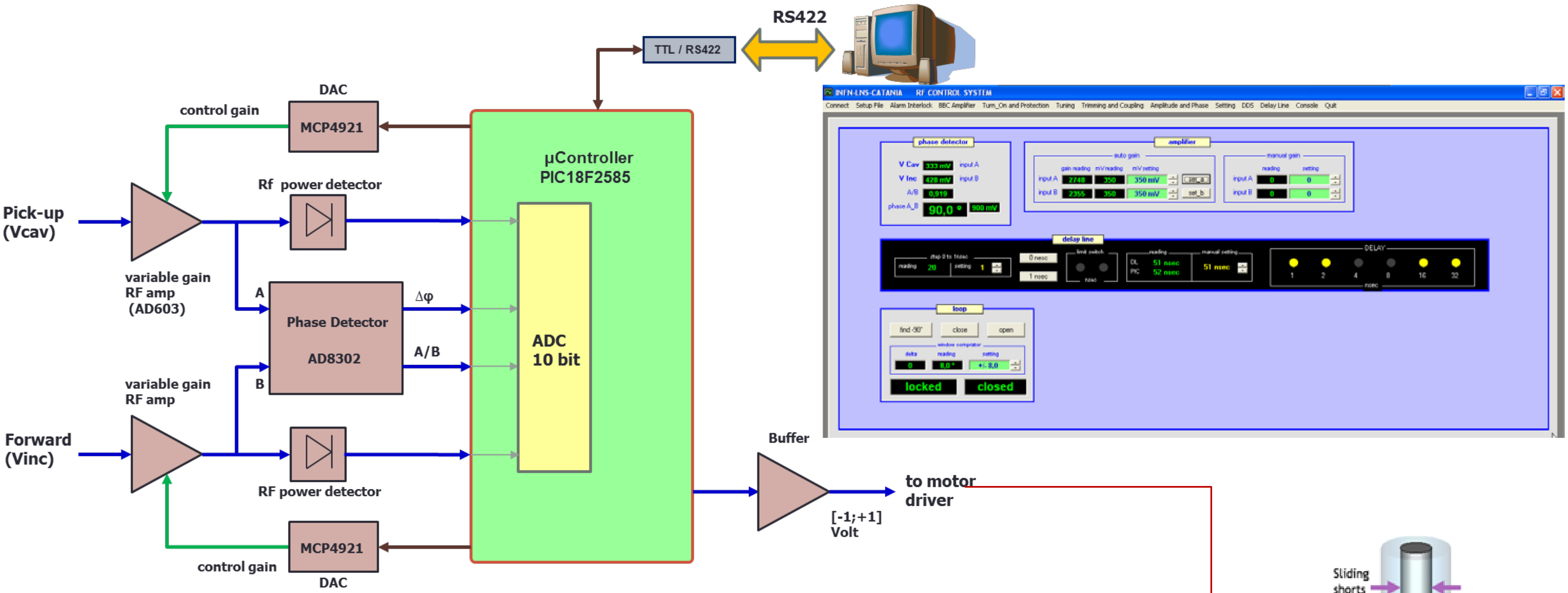
Fine tuning loop

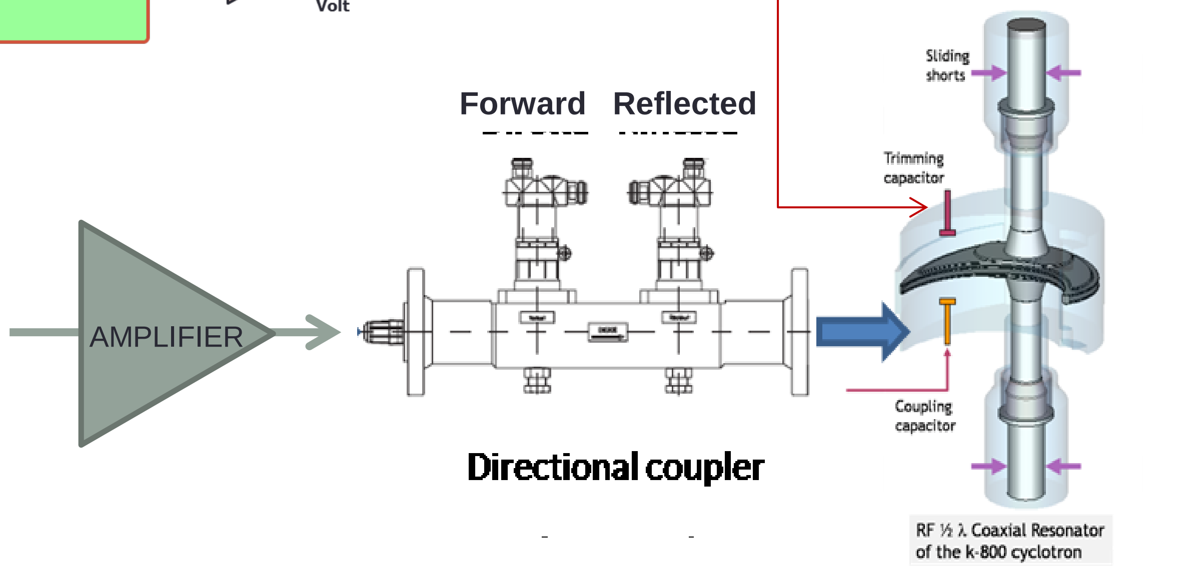


Digital/Analog tuning loop



Courtesy of A. Longhitano





This new automatic tuning loop system is succesfully installed on the axial buncher matching box. IT WILL BE INSTALLED ON THE LLRF CYCLOTRON SOON

Conclusion remarks

- RF power amplifier refurbishment, solid state + tube
- LLRF from analog to analog/digital to full digital
- Upgrade Superconducting Cyclotron (increase the final RF amplifier power of 20-30%, new conical connection between inner coaxial and dee, adaptation of the already versatile low level system), preparation phase of dismounting cavities and RF parts involved.

Working Group

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Thank you for your kind attention

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[10] A. Caruso, The RF system of the K-800 superconducting cyclotron at INFN-LNS, Indian Particle Accelerator Conference, 2013, VECC, Kolkata;
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